DESIGN AND STUDY OF MODEL REFERENCE ADAPTIVE PSS & SVC STABILIZERS FOR DYNAMIC STABILITY

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CERTIFICATE

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CONTENTS

ABSTRACT

This thesis is concerned with design of Model Reference Adaptive PSS and SVC Stabilizers and study of their operation in both singular and simultaneous operations. Lyapunov's criterion has been used to ensure overall System Stability. Since all the states are not available for measurement, observers are designed to estimate the unknown states.

With the help of speed input MRAPSS it has been shown that the controllers work for large changes around the operating point too, provided these changes take place very slowly.

LIST OF FIGURES

LIST OF PRINCIPAL SYMBOLS

p	Differential operator d/dt
Δ	Prefix to denote small changes about the operating point.
o	Subscript to denote the value of the operating point.
t	Time in seconds.
ω_o	Synchronous angular velocity in radians per second.
ω	Instantaneous angular velocity of rotor in radians per second.
δ	Rotor angle with respect to system reference in radians.
V_∞	Infinite bus voltage magnitude in p.u.
V_t	Generator terminal voltage magnitude in p.u.
V_m	Transmission line midpoint voltage in p.u.
V_d, V_q	d and q axes components of V_t.
V_{md}, V_{mq}	d and q axes components of V_m.
I_d, I_q	d and q axes components of stator current.
X_d, X_q	d and q axes synchronous reactances.
X_d'	d axis transient reactance.
T_{do}'	d axis transient open circuit time constant.
H	Inertia constant in seconds
M	$\frac{2H}{\omega_o}$
K_D	Damping coefficient
E_{FD}	Generator field voltage in p u
P_e	Generator electrical power output in p.u

T_e	Electrical torque developed
T_m	Mechanical torque input.
R	Half line resistance
X	Half line reactance
B	SVC suceptance.
K_A	Exciter voltage regulator gain
T_A	Exciter voltage regulator time constant.
K_B	SVC voltage regulator gain
T_B	SVC voltage regulator time constant.

CHAPTER - 1

INTRODUCTION

1 1 GENERAL

Enhancement of stability is an important task in improving the quality and reliability of power system. Power system engineers are mainly concerned with three type of stability:-

1 Static stability, which limits the maximum power transfer capability of the system.
2. Transient stability, which indicates the capacity of the system to withstand major shocks
3. Dynamic stability, which is the capability of system to adjust to small perturbation in the system operating condition.

Modern trend in improvement of transient stability is the use of fast action, high gain AVR's with static excitation system in modern alternators They, however, have deleterious effect on dynamic stability limit of the power system, but they have deleterious effect on dynamic stability, resulting often in lightly damped and even sustained oscillations, typically in the range of 2 to 2 Hz [1,2]

Extensive study in this field started with the paper of De Mellow and Concordia [3] which explained the problem of dynamic stability in terms of the concepts of synchronous and damping torques. Thyristor type excitation introduces negative damping in

the system. To offset this effect and to improve damping in general, modern systems have auxiliary networks in the excitation system. These additional stabilizing networks essentially modulate reactive power to improve dynamic stability of the system. Another method of damping low frequency oscillations is to use SVC stabilizer. Though the main function of SVC is to regulate voltage, it has been found that a significant contribution to system damping is achieved when an appropriate auxiliary feedback network is introduced in the control scheme. The stabilizing signal from this network essentially modulates the reactive power in the system.

1 2 REVIEW OF LITERATURE

1 2.1 Power System Stabilizers (PSS)

Extensive research has been done in the application of PSS for improvement of dynamic stability There are two types of PSS reported in the literature -

(i) Non adaptive PSS

(ii) Adaptive PSS

1.2.1.1 Non adaptive PSS

Here the PSS structure and parameters will not change with time or operating conditions or system configuration Their operation may not be satisfactory over a wide range operating conditions The methods use pole placement and optimization

techniques. An extensive list of works falling in this category is reported in [4,5]

1.2 1 2 Adaptive PSS

All major techniques namely, self tuning regulators (STR), gain scheduling schemes, variable structure control and model reference adaptive control; (MRAC) have been considered for adaptive PSS design These stabilizers are designed to give satisfactory system performance over wide range of operating conditions

Self tuning regulator (STR) techniques are digital adaptive control schemes and involve parameter estimation and control. Most of the works use recursive least square techniques (RLC) for parameter estimation Reference [6] and [7] give an account of work carried out in this area

Gain scheduling schemes require extensive off line simulations A simple adaptive PSS using gain scheduling approach has been developed by the Brown Boveri Company [8]. Bandopadhyay and Prabhu [9] have designed five different constant gain PSS for five operating conditions and used them simultaneously to operate in parallel. At any operating point, the control signal for stabilization is obtained as a weighted sum of outputs of individual PSS. Recently, Madhu and Prabhu [10] have proposed design of robust adaptive composite PSS which makes use of gain scheduling schemes

Variable structure schemes essentially use nonlinear

feedback control In these schemes structure of feedback changes depending on the position of state point. Ref. [11] and [12] contain some work in this area

MRAC techniques has now been gaining popularity. Irving et al [13] described MRAC for generator voltage regulation based on maintaining an unconditionally stable adaptive loop using Popov's hyperstability theory. Ibrahim and Kamel [14] have proposed a Model reference PSS (MRAPSS), which suffers from practical constraints of design. Ghaondkly and Idowu [15] have presented a decentralized MRAC scheme for design of PSS and a means for coordinating the generator unit excitation and governor control loop. Recently Aruna Kumari and Prabhu [16] have designed a model reference adaptive PSS, which uses Lyapunov's criterion to assure overall system stability.

1 2.2 SVC Stabilizers

Application of SVC for the improvement of dynamic stability is a recent development Kinoshita [17] has reported the improvement of dynamic stability by auxiliary modution of SVC reactive power. Padiyar et.al [18] have demonstrated that significant improvement in dynamic stability can be achieved by auxiliary stabilizing signal. Varma [19] and Raman et al [20] have studied the effects of SVC stabilization on dynamic stability of a power system with a long transmission line. Not much literature is available on design of SVC stabilizers.

1 2 3 Coordinated Operation of PSS and SVC Stabilizers

Very few research reports are available on coordinated application of PSS and SVC Hamouda et.al [21] have discussed the technical advantage of coordinating SVC and PSS for damping inertial and torsional modes of steam turbine generators, locating SVC at generator bus. Cheng et al [22] have discussed the application of PSS and SVC for a multi machine power system. Sharma and Prabhu [23] have recently shown the advantages of coordinating PSS and SVC stabilizers.

1 2 4 Location of SVC

Location of SVC in power system for improvement of dynamic stability is important. Hamouda et al [21] have discussed the dynamic stability enhancement by locating SVC at generator bus Kinoshita [17], Varma [19] and Raman [20] have suggested midpoint of transmission line for locating SVC as it also increases power transfer capability of transmission line a part from improvement in dynamic stability.

1 3 OBJECTIVES AND SCOPE OF THE THESIS

This thesis is mainly concerned with design of MRA PSS and MRA SVC stabilizers and their coordinated operation for improvement of dynamic stability of the power system. Main objectives of this thesis work are -

1. To develop a suitable model for the power system in a sufficiently simple form consisting of a generator

connected to an infinite bus through a transmission line and SVC located at the mid point of transmission line.

2. To design a MRA PSS with a satisfactory performance over wide range of operating points, assuming that only SVC voltage controller is in the system and the SVC stabilizer is not present

3. To design a MRA SVC stabilizer with a satisfactory performance over wide range of operating points, assuming that PSS is not present in the system.

4. To use the simultaneous operation of MRAPSS and MRASVC stabilizer to improve the dynamic stability of the system

1.4 OUTPUT OF THE THESIS

A chapter wise summary of the work done in this thesis is given below -

In chapter 2, the system model for dynamic stability study has been developed Output equations corresponding to PSS using power and speed signals are developed Similarly output equations corresponding to SVC using mid line active power and mid line reactive power have also been developed

In chapter 3, a brief introduction to model reference adaptive system (MRAS) and their design methodologies is given. State feedback MRAC using Lyapunov synthesis techniques is also presented

In chapter 4, MRAPSS and MRASVC stabilizers are designed Lypunov's criterion has been used to ensure overall system stability. Since all the states are not available for measurement, observers are designed to estimate the unknown states. A effort to coordinate these stabilizers is also presented Simulation studies are around the design point and are limited to small variations

In chapter 5, with the help of speed input MRAPSS it has been shown that the controller works for large changes in the operating point provided these changes take place slowly. The demonstration is by simulation of the Power System with the adaptive PSS

In chapter 6, results and suggestions for further work are presented

CHAPTER - 2

MODEL OF POWER SYSTEM

2 1 INTRODUCTION

Importance of PSS and SVC in damping electromechanical oscillations in the system is well established Linearized state space model is used for studying dynamic stability behaviour of the power system.

The power system in its simplest form consists of synchronous generator connected to an infinite bus through a transmission line In the literature various state space models of the system having varying degrees of accuracy are available Of these models, Heffron - Phillip Model [24] has been used by many researchers because of its simplicity adequate accuracy and ability to offer good physical understanding of the system while taking the demagnetising effect of armature reaction into consideration It neglects the fast dynamics associated with the damper windings since these are not of importance in dynamic stability studies. Heffron - Phillip Model and the slightly more complex '1 5 model' [25] become the standard models for dynamic stability studies. There are, however, problems, for example those associated with subsynchronous resonance (SSR), where more detailed models would be needed

We for our study in this thesis, have considered Heffron Phillip Model, as it is adequate for the purpose of dynamic stability study involving mainly the slow electromechanical and

exciter mode of behaviour

2 2 DEVELOPMENT OF SYSTEM MODEL

The state space model of the system is developed on lines similar to [24]

The synchronous generator is connected to an infinite bus through a transmission line and SVC is installed at the midpoint of the transmission line as shown in Fig. 2 1

The following assumptions are made for developing the state space model of the system given in Fig. 2.1.

1 The synchronous generator has no damper windings.

2 Governor -turbine dynamics can be ignored.

3 A T-model of transmission line is sufficient The line charging suceptance is clubbed with SVC suceptance

4 The machine stator and external network are in quasi-steady state.

5. Saturation in generator is neglected.

2 2.1 Generator Model

A third order generator model is considered In the equation given below the standard notations are used

The dynamical equation corresponding to generator field circuit can be written as [25]

$$p\ Eq' = -\frac{E_{q'}}{T'_{d_o}} + \frac{E_{FD}}{T'_{d_o}} + (Xd - Xd')Id \qquad (2.1)$$

The dynamical equation corresponding to the generator

swing equation can be written as

$$p\omega = \frac{1}{M}(T_m - T_e) - \frac{K_D}{M}(\omega - \omega_o) \tag{2.2}$$

$$p\delta = \omega - \omega_o \tag{2.3}$$

where,

$$M = \frac{2H}{\omega_o} \tag{2.4}$$

$$Te = (V_d I_d + V_q I_q) \tag{2.5}$$

In the above equations δ and ω are in radians and radians/sec The rest of the quantities are in p u

2 2 2 Excitation System

IEEE Type 1S [26] model of excitation system is considered Fig 2.2 gives a block diagram of this system.

The dynamical equation representing the excitation system is,

$$p\, E_{FD} = -\frac{E_{FD}}{T_A} + \frac{K_A}{T_A}(V_{ref} - V_t + V_{ss}) \tag{2.6}$$

where V_t is the generator terminal voltage. It can be represented in terms of Park's voltage as

$$V_t^2 = V_d^2 + V_q^2 \tag{2.7}$$

where,

$$V_d = X_q\, I_q \tag{2.8}$$

$$V_q = X_d'\, I_d + E_q' \tag{2.9}$$

2.2 3 Static Var Compensators (SVC)

SVC is normally a combination of reactors and capacitors, controlled by thyristor circuits. Different types of SVC configurations are used in practice. They are mainly :

1. Fixed capacitor and thyristor controlled reactor (FC-TCR).

2. Thyristor switched capacitor and thyristor controlled reactor (TSC-TCR)

These configurations are shown in Fig 2 3. The main objective of SVC is to control the voltage at a bus by modulation of reactive power which is achieved by varying the thyristor firing angle This varies the fundamental current flowing through the reactor and consequently makes the reactor to effectively act as a variable reactance device The general control scheme of SVC is shown in Fig. 2.4.

We have considered a simple first order regulator shown in Fig 2 5

The dynamical equation representing SVC voltage controller is

$$pB = -\frac{B}{T_B} + \frac{K_B}{T_B}(V_{m\ ref} - v_m + V_{se}) \qquad (2.10)$$

2.2 4 Linearized Model

The linearized state space model of the power system is obtained by linearizing equations (2 1), (2 2), (2.3), (2.6) and (2.10). The non state variables ΔI_d, ΔV_t, ΔT_e and ΔV_m are then eliminated using the following expression [derivation given in Appendix - A]

$$\begin{bmatrix} \Delta Id \\ \Delta Iq \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{bmatrix} \begin{bmatrix} \Delta Eq' \\ \Delta\delta \\ \Delta B \end{bmatrix} \qquad (2.11)$$

Where parameters b11, b12----- b23 are defined in Appendix - A

The resulting fifth order system model is described by the state equation

$$p\underline{X} = A\underline{X} + \underline{b}_1 u_1 + \underline{b}_2 u_2 \tag{2.12}$$

where $\underline{X} = [\Delta Eq' \ \Delta\omega \ \Delta\delta \ \Delta E_{FD} \ \Delta B]^t$ (2.13)

$u_1 = \Delta V_{ss}$ Stabilizing signal from PSS (2.14)

$u_2 = \Delta V_{se}$, Stabilizing signal from SVC stabilizer (2.15)

The matrices A, b1 and b2 are as given below ·

$$A = \begin{bmatrix} A_{11} & 0 & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & 0 & A_{25} \\ 0 & A_{32} & 0 & 0 & 0 \\ A_{41} & 0 & A_{43} & A_{44} & A_{45} \\ A_{51} & 0 & A_{53} & 0 & A_{55} \end{bmatrix} \tag{2.16}$$

$$\underline{b}_1 = [0 \ 0 \ 0 \ b_4 o]^t \tag{2.17}$$

$$\underline{b}_2 = [0 \ 0 \ 0 \ 0 \ b_5]^t \tag{2.18}$$

The parameters A11, - - - - - A55 and b4, b5 in the above equations are given in Appendix - A.

2.2.5 Development of output equations

The output equation of the system in general can be written as

$$y_1 = C_1 \underline{x} \tag{2 19}$$

where y_1 represents input signal to PSS and

$$y_2 = C_2 \underline{x} \tag{2.20}$$

where y_2 represents the input signal to SVC stabilizer The elements of the matrices C_1 and C_2 depend upon the actual variables y_1 and y_2 chosen

2.2 5.1 Output equations corresponding to PSS input signals

For PSS we have considered generator active power and rotor speed as control signals.

Power Signal

Generator active power is given by

$$P_e = V_d I_d + V_q I_q \tag{2.21}$$

In p u $P_e = T_e$ (where P_e and T_e are p u three phase power and torque, respectively).

Hence $$\Delta P_e = \Delta T_e \tag{2.22}$$

The output equation corresponding to power signal input PSS is then,

$$y_1 = [\Delta P_e] = [b_{40} \quad 0 \quad b_{41} \quad 0 \; b_{42}] \; \underline{x} \tag{2.23}$$

Hence $$c_1 = [b_{40} \quad 0 \quad b_{41} \quad 0 \; b_{42}] \tag{2 24}$$

Where parameters b_{40}, b_{41} and b_{42} are given in Appendix A.

Speed Signal

Here change in rotor speed ($\Delta\omega$) is used as PSS input signal Since speed is one of the state variables in our system model, the output equation is directly obtained as

$$y_1 = [\Delta\omega]$$

$$= [0 \quad 1 \quad 0 \quad 0 \quad 0]\ \underline{x} \tag{2 25}$$

Hence $$c_1 = [0 \quad 1 \quad 0 \quad 0 \quad 0] \tag{2.26}$$

2 2 5.2 Output Equations Corresponding to SVC Stabilizer input Signals

For SVC stabilizer we have considered midline power and midline reactive power signals.

Midline Power Signal:

The midline power is given by

$$P_m = [V_{md}\ I_d + V_{mq}\ I_q] \tag{2.27}$$

Linearizing the above expression and expressing ΔI_d and ΔI_q in terms of state variables, we get

$$\Delta P_m = b_{60}\ \Delta E_{q'} + b_{61}\ \Delta\delta + b_{62}\ \Delta B \tag{2.28}$$

Thus we can write

$$y_2 = [\Delta P_m]$$

$$= [b_{60} \quad 0 \quad b_{61} \quad 0 \ b_{62}]\ \underline{x} \tag{2.29}$$

Hence $$c_2 = [b_{60} \quad 0 \quad b_{61} \quad 0 \ b_{62}] \tag{2.30}$$

The parameters b_{60}, b_{61} and b_{62} are given in Appendix A

Midline Reactive Power Signal:

Midline reactive power is given by

$$Q_m = [V_{md}\ I_q - V_{mq}\ I_d] \tag{2.31}$$

Linearizing the above expression and manipulating we get

$$\Delta Q_m = b_{80}\ \Delta E_{q'} + b_{81}\ \Delta\delta + b_{82}\ \Delta B \tag{2.32}$$

Thus we can write

$$y_2 = [\Delta Q_m]$$

$$= [b_{80} \quad 0 \quad b_{81} \quad 0 \quad b_{82}] \ \underline{x} \qquad (2.33)$$

Hence $\quad c_2 = [b_{80} \quad 0 \quad b_{81} \quad 0 \quad b_{82}] \qquad (2.34)$

The parameters b_{80}, b_{81} and b_{82} are given in Appendix A.

2.3 NUMERICAL EXAMPLE

The power system data that we have considered in this thesis are as in ref [17], except for the excitation system data. The system is as shown in Fig 2.6

The generator represented in Fig 2 6 is the equivalent generator representing all the generators of a generating station. The generator capacity is 5000 MVA The power is transmitted over a distance of 200 km by a 500 kV two double circuit transmission lines (4 lines in parallel, in all) and SVC is installed at the midpoint of the transmission line The power system data is given in Appendix B

We have chosen the infinite bus as the reference bus. The SVC bus voltage is specified as 1 02 p u. Assuming that the generator is operating at rated capacity at power factor lagging, load flow is run to compute the generator terminal conditions and the SVC voltage angle

The A, b_1 and b_2 matrices of the system at the above operating point are,

$$A = \begin{bmatrix} -0\ 5283 & 0 & -0\ 277 & 0\ 156 & 0.0296 \\ -35.53 & 0 & -54\ 59 & 0 & -0.8217 \\ 0 & 1 & 0 & 0 & 0 \\ -1212\ 4 & 0 & -9\ 64 & 100\ 0 & -408\ 98 \\ -59\ 07 & 0 & 14\ 48 & 0 & -148\ 76 \end{bmatrix} \qquad (2\ 35)$$

$$b_1 = [0 \quad 0 \quad 0 \quad 5000 \quad 0\ ]^t \qquad (2.36)$$

$$b_2 = [0 \quad 0 \quad 0 \quad 0 \quad 1000]^t \qquad (2.37)$$

The open loop eigenvalues corresponding to the above A matrix are -148 54, -98 85, -1.97, - 0.108±j 7 3667.

2.4 CONCLUDING REMARKS

In this chapter, a state space model of a single machine infinite bus system with SVC located at midpoint of transmission line is presented. The output equations corresponding to the various input signals of the stabilizers are developed. A numerical example is also presented.

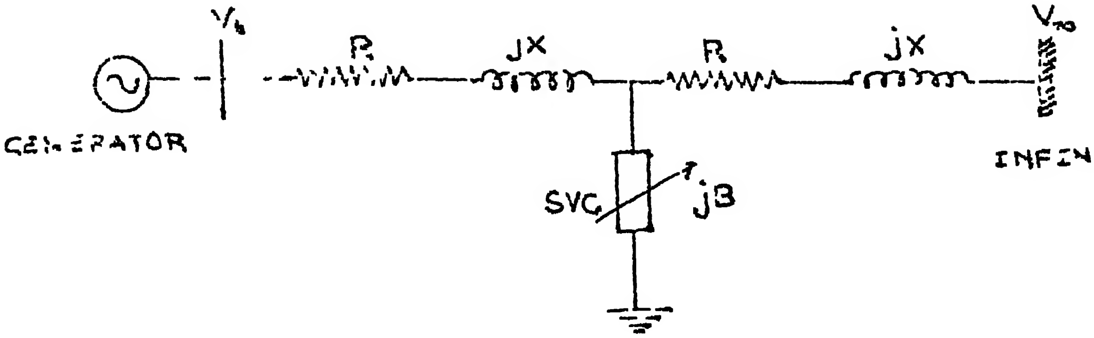


FIG. 2.1 : SINGLE MACHINE INFINITE BUS SYSTEM WITH SVC

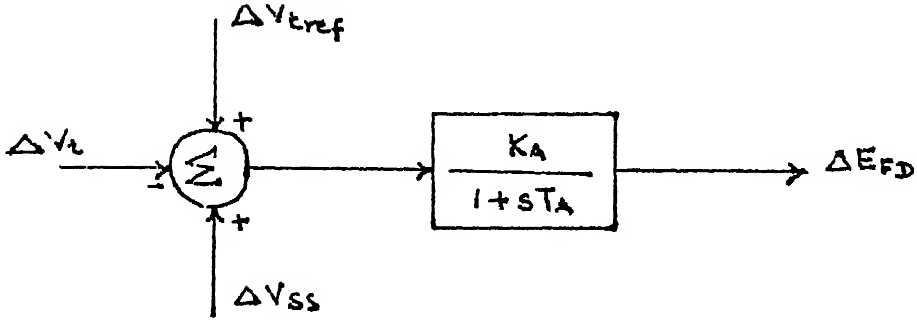
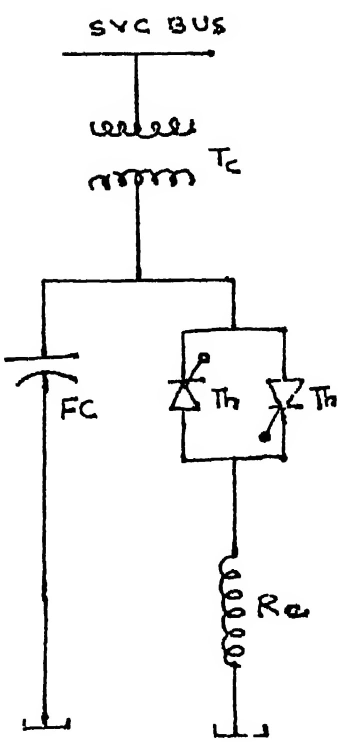
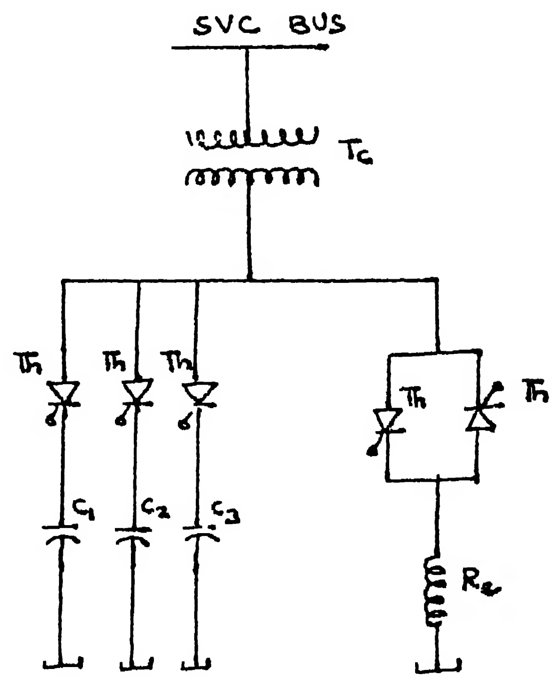


FIG. 2.2 : IEEE TYPE-1S EXCITATION SYSTEM



FC-TCR



TSC-TCR

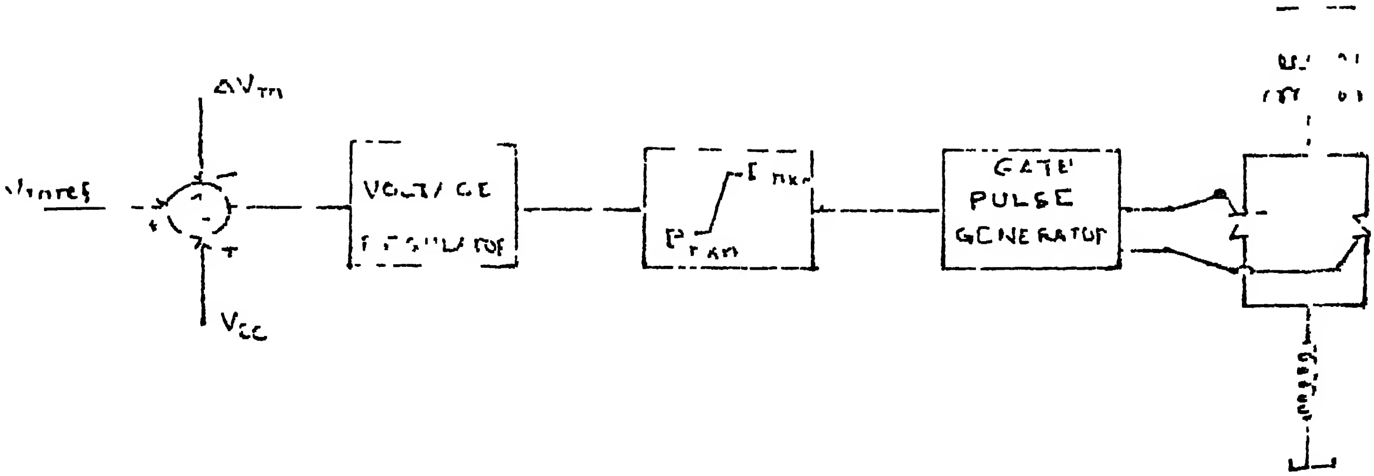


FIG 24 : GENERAL CONTROL SCHEME OF SVC

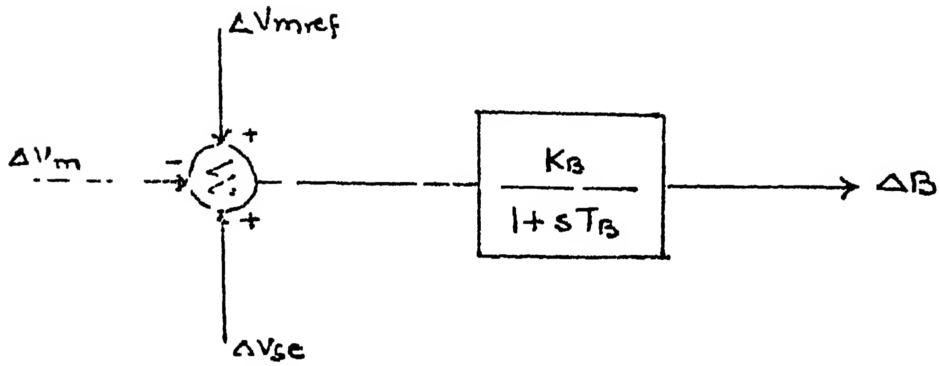


FIG 25 : BLOCK DIAGRAM REPRESENTATION OF SVC CONTRO

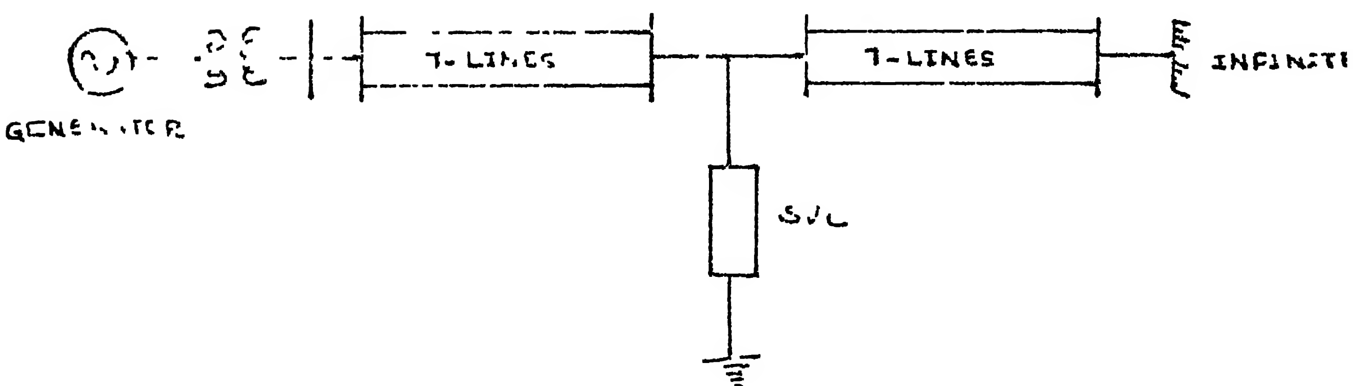


FIG 26 : STUDY SYSTEM

CHAPTER - 3

FUNDAMENTALS OF MRAC TECHNIQUE

3 1 INTRODUCTION [27]

In MRAC, the aim is to make the states (or outputs) of unknown plant approach asymptotically the states (or outputs) of a given reference model in which desired system characteristics are incorporated. The difference between the states of the reference model and those of the adjustable system is used by the adaptation mechanism either to modify the parameters of adjustable system (called parameter adaptation) or to generate an auxiliary input signal (called signal synthesis adaptation) in order to minimise the difference between the states of the adjustable system and those of the model. The basic scheme of MRAC is shown in Fig. 3 1.

3 2 CLASSIFICATION OF MRAS

In terms of controller structure MRAS are classified into three types .-

1. Series MRAS :Adjustable system and reference model in series (Fig 3.2 (a)).

2. Series Parallel MRAS :

   (i) Reference model in two parts, one in series with adjustable system and other in parallel (Fig 3 2 (b)).

   (ii) Adjustable system in two parts, one in series with

reference model and other in parallel (Fig. 3.2 (c)).

3. Parallel MRAS : Reference model in parallel with adjustable system (Fig 3 2 (d))

We have used parallel MRAC structure which is the most commonly used one

3.3 DESIGN METHODOLOGIES

There were three important techniques for the design of continuous time MRAC, namely the MIT rule and related methods, the Lyapunov approach and Popov's hyperstability approach.

3 3.1 MIT Rule

In MIT rule, the input u (t) of the system is applied to appropriately designed reference model to generate the desired output The integral of the square of the error between this desired output and the output of the plant is minimized.

The performance index (PI) is given by

$$J = \int_0^T \| \underline{y}_m(t) - \underline{y}(t) \|^2 dt \qquad (3.1)$$

where $\underline{y}_m$ is the output of the reference model and $\underline{y}$ is the output of the adjustable system.

Many improvements in the structure of PI and its on line evaluation have been suggested

MIT rule has the advantage of simplicity in implementation Main drawbacks of MIT rule are :

1 Low speed of adaptation

2 No assurance of system stability

3 Requires difference between parameters of reference model and those of adjustable system to be small.

3.3 2 Lyapunov Approach

In Lyapunov approach, the first step is to determine the differential equation of error between states of reference model and adjustable plant. Then the parameter adjustment equations are obtained as the conditions to assure the stability of the error differential equation In order to do this, a positive definite Lyapunov function is chosen Then, the adaptation mechanism equations are derived so as to cause the time derivative of the Lyapunov function to be negative semidefinite This negative semi definiteness of the Lyapunov function ensures system asymptotic stability, i e, the error goes to zero, as $t \rightarrow \infty$.

The main difficulties of Lyapunov approach are .

1. Entire state vector must be available for measurement which is not always possible

2. Design rule may not be applicable if plant parameters cannot be directly adjusted.

3 3.3 Hyperstability Approach

For application of hyperstability approach, the MRAC system (MRAC) is expressed as a standard system (Fig 3.3), with a

linear time invariant operator in the forward path and a passive nonlinear operator in the feedback path The nonlinear operator satisfies Popov Integral Inequality [28] The system is then asymptotically hyperstable if the transfer function matrix of the linear block is strictly positive real. To apply this approach to MRAS, it is necessary to express the error equation in the standard form Hyperstability conditions enable determination of feedback block N, which constitutes the adaptation law.

3.4 STATE FEEDBACK MRAC USING LYAPUNOV SYNTHESIS TECHNIQUE [29]

The basic configuration of state feedback MRAS is shown in Fig 3 4.

The state equation of stable reference model is

$$X_m = A_m X_m + B_m r \tag{3.2}$$

and that of linear time invariant plant is

$$X = A X + B u \tag{3.3}$$

Here X_m and X are n - dimensional state vectors and r and u are m - dimensional control vectors.

The state error vector is defined as

$$e = X_m - X \tag{3.4}$$

The differential equation of error is given by

$$e = A_m e + f \tag{3.5}$$

where

$$f = (A_m - A) X + B_m r - Bu \tag{3.6}$$

In order to drive the state error vector to zero by feedback synthesis using Lyapunov's direct method, a positive definite function of the form

$$V = e^t Pe + h(\vartheta,\psi) \tag{3.7}$$

is selected as a candidate Lyapunov function where P is a symmetric positive definite matrix and $h(\vartheta,\psi)$ is functional expression for misalignment between the reference model parameters and the plant parameters. Misalignment parameters vectors ϑ,ψ are defined in terms of elements of matrices $(A_m - A)$ and $(B_m - B)$ respectively.

The control objective for a stable system is to specify a control law such that the first derivative of candidate Lyapunov function, V is negative semi definite. This implies the stability of error system

Now let us have a state feedback of KX and a feed forward of Σu for the plant In that case, the plant state equation, with the above control incorporated, becomes

$$X = (A + B \Sigma K)X + B \Sigma u \tag{3.8}$$

For exact model matching, we need existence of matrices K^* and Σ^* such that

$$B\,\Sigma^* = B_m \tag{3.9}$$

$$A + B_m K^* = A_m \tag{3.10}$$

It is assumed that both B_m and B are of full rank so that Σ^* is non singular The equation satisfied by state error vector, e, is

$$e = A_m e + (A_m - A - B\,\Sigma\,K)X + (B_m - B\,\Sigma)u \tag{3.11}$$

It can be shown [29] that above equation can be expressed as

$$e = A_m e + B_m \vartheta X + B_m \psi\,\Sigma(r + Kx) \tag{3.12}$$

where

$$\vartheta = [K^* - K(t)] \text{ and}$$

$$\psi = [\Sigma^{-1}(t) - \Sigma^{*-1}] \tag{3.13}$$

For the error equation, we choose

$$V = \frac{1}{2}\,[e^t P e + tr\{\vartheta^t \Gamma_1^{-1}\,\vartheta + \psi^t \Gamma_2^{-1} \psi\}] \tag{3.14}$$

where,

$$\Gamma_1 = \Gamma_1^t > 0 \text{ and}$$

$$\Gamma_2 = \Gamma_2^t > 0 \text{ and} \tag{3.15}$$

It can be derived {], that if we have

$$\vartheta = -\,\Gamma_1\, B_m^t\, Pe\, x^t \text{ and}$$

$$\psi = - \Gamma_2 B_m^t \ Pe\ (r + Kx)^t \Sigma^t \tag{3 16}$$

the stability of equation (3.12) in the (e, ϑ, ψ) space is guaranted In the above equation P is a positive definite matrix satisfying

$$A_m^t P + PA_m = -Q \qquad Q = Q^t > 0 \tag{3.17}$$

The adaptive control law in terms of K(t) and $\Sigma(t)$ is

$$K(t) = \Gamma_1 B_m^t \ Pe\ x^t$$

$$\Sigma(t) = \Sigma \Gamma_2 B_m^t \ Pe\ (r + Kx)^t \Sigma^t \Sigma \tag{3.18}$$

For ensuring stability, it is necessary to start with sufficiently small vale of $e(t_o)$, $K^* - K(t_o)$ and $\Sigma^* - \Sigma(t_o)$.

3 5 CONCLUDING REMARKS

In this chapter a basic introduction to Model Reference Adaptive Systems (MRAS) has been presented. State feedback MRAC using lyapunov synthesis technique has been discussed in detail. It will be used in next chapter for design of stabilizers.

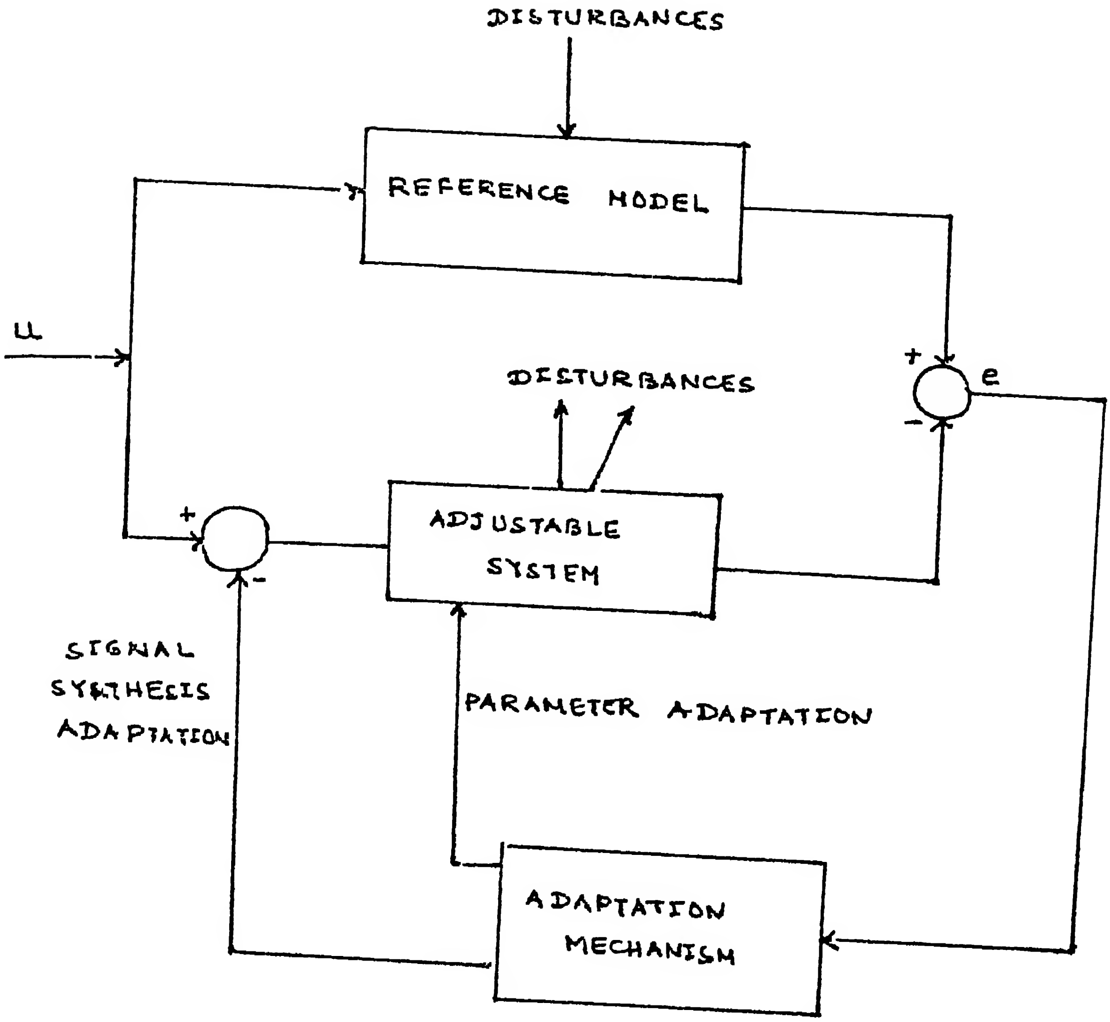


FIG. 3.1 : BASIC CONFIGURATION OF A MRAS

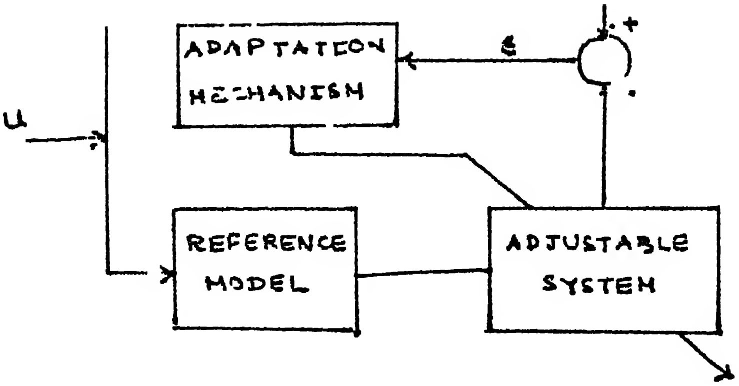


FIG. 3.2 (a) : SERIES MRAS

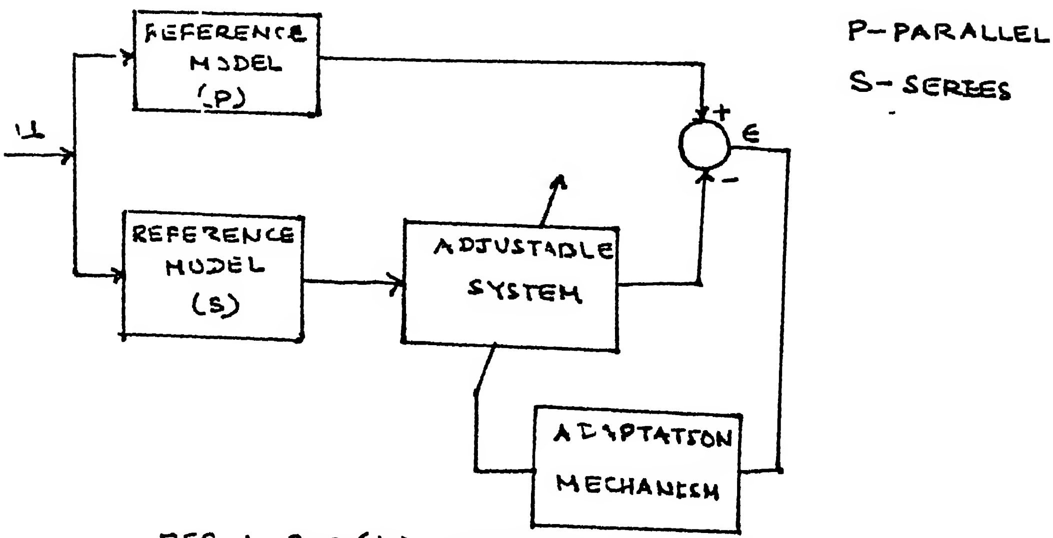


FIG. 3.2 (b) SERIES PARALLEL MRAS

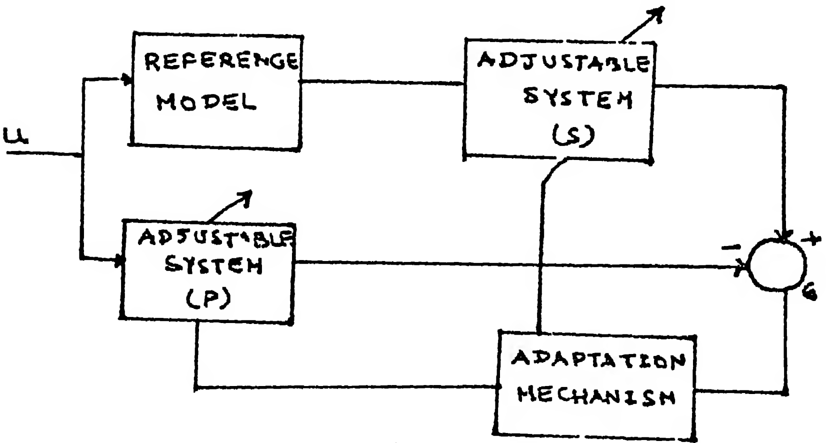
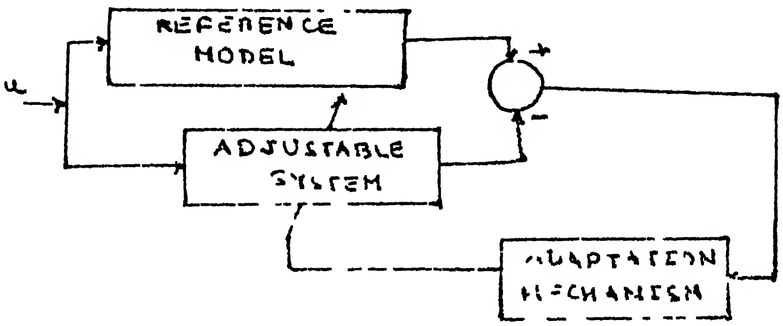


FIG. 3 2 (c) : SERIES PARALLEL MRAS



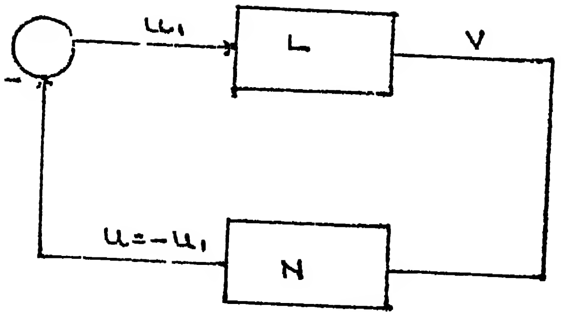


FIG 3 3 : STANDARD FEEDBACK SYSTEM (HYPERSTABILITY APPROACH)

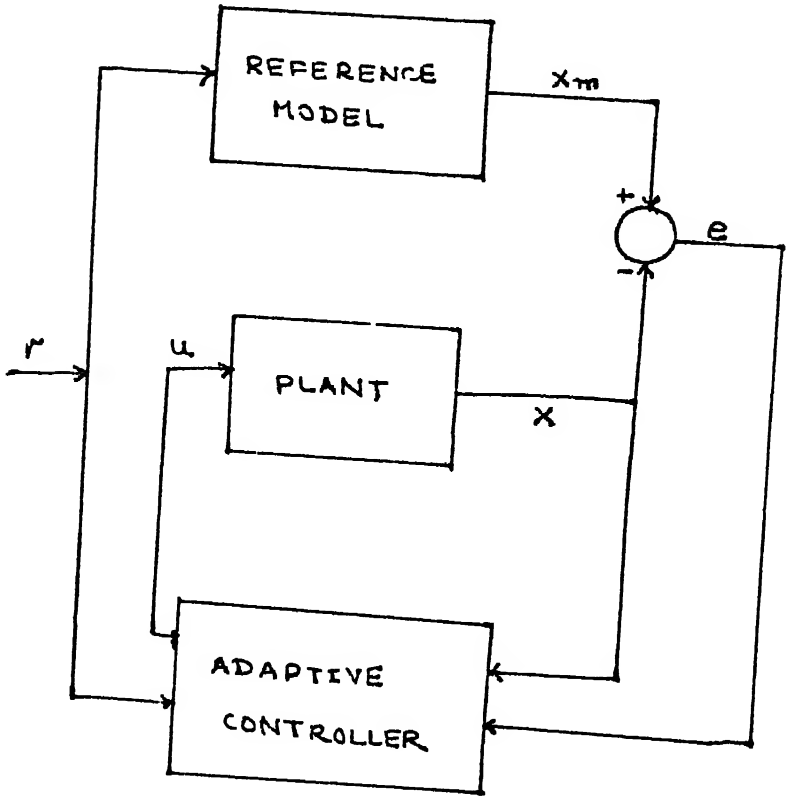


FIG 3 4 : BASIC CONFIGURATION OF STATE FEEDBACK MRACS

CHAPTER - 4

DESIGN OF MODEL REFERENCE ADAPTIVE STABILIZERS

4 1 INTRODUCTION

A design methodology, which involves application of MRAC concept for design of stabilizers has been presented in Chapter 3. In the proposed scheme, a reference model into which desigr specifications are included is introduced and states of plant are forced to follow states of reference model. Since all the states may not be available for measurement, observers are designed to reconstruct them. Simulation results are also presented

4 2 SECTOR CRITERION FOR CLOSED LOOP POLE LOCATIONS

From the open loop eigenvalues presented in sec.2.3 we observe that there is a pair of complex eigenvalues which correspond to the electromechanical mode of oscillation of the system The real part of these eigenvalues is close to the imaginary axis in s - plane indicating insufficient damping in the system The main objective of stabilizer is to shift these eigenvalues to a more stable location in s - plane. The damping provided depends upon the locations of these eigenvalues.

A sector as shown in Fig. 4.1 is chosen for placing the reference model poles. Within this sector the damping ratio of dominant eigenvalues will be better than 0.0735 which is adequate for the power system

4.3 PROBLEM FORMULATION

The state space model of the power system for the purpose of PSS design has the following form

$$X = Ax + Bu \tag{4.1}$$

Where A is 5 x 5 matrix, B is 5 x 1 matrix, x is 5 x 1 vector and u is the scalar input.

The reference model is presented as

$$x_m = A_m \, x \, m + B_m r \tag{4.2}$$

The state variables in the above equation are

$$X = [X_1 \;\; X_2 \;\; X_3 \;\; X_4 \;\; X_5\,]^t = [\Delta E\, q'\, \delta\omega \;\; \Delta\delta \;\; \Delta E_{FD} \;\; \Delta B\,]^t \tag{4.3}$$

$$X_m = [X_{m1}\; X_{m2}\; X_{m3}\; X_{m4}\; X_{m5}]^t = [\Delta E_m q'\, \delta\omega_m \;\; \Delta\delta_m \;\; \Delta E_{FDm} \Delta B_m]^t \tag{4.4}$$

The control matrices B and B_m are

$$B = B_m = [0 \;\; 0 \;\; 0 \;\; b_4 \;\; 0] \text{ for PSS}$$

$$= [0 \;\; 0 \;\; 0 \;\; 0 \;\; b_5] \text{ for SVC stabilizer} \tag{4.5}$$

From the derivation of the power system model given in Appendix A, it is clear that as the operating conditions defined by complex power supplied by the generator changes, only the matrix A changes and the matrix B is unaffected. Thus, it is not necessary to have the feed forward term Σu in the design as given

earlier and the adaptive control becomes

$$u = K(t)x + r \qquad (4.6)$$

where u represents the control input to the plant. The closed loop system becomes,

$$X = (A + BK)x + Br \qquad (4.7)$$

The matrix K is given by

$$K(t) = \Gamma(B_m^t\ Pe)x^t \qquad (4.8)$$

where

Γ is a symmetric positive definite matrix

P is symmetric positive definite and satisfies the Lyapunov equation.

A_m is to be chosen such that it ensures the asymptotic stability of the reference model.

4.4 DESIGN AND SIMULTANEOUS OPERATION OF STABILIZERS

4.4.1 MRAPSS design

4 4 1 1 Selection of Reference Model

The matrix A_m of the reference model is selected such that the poles of the system are placed in the permissible sector shown in Fig 4 1.

For the numerical problem considered in Chapter 2,

$$A = \begin{bmatrix} -0\ 5283 & 0 & -0.277 & 0.156 & 0\ 0296 \\ -35.53 & 0 & -54.59 & 0 & -0.8217 \\ 0 & 1 & 0 & 0 & 0 \\ -1212\ 4 & 0 & -9.64 & -100 & -408.98 \\ -59\ 07 & 0 & 14\ 48 & 0 & -148.76 \end{bmatrix} \quad (4.9)$$

and $B = [0 \quad 0 \quad 0 \quad 5000 \quad 0]$

The open loop poles of the system are

$-148\ 54,\ -98\ 85,\ -1.97,\ -0\ 108 \pm j\ 7.3667.$

We specify that A_m should have eigenvalues at -148.54, $-98\ 85$, $-1\ 97$ and $-1\ 5 \pm j\ 7.3667$

We find that A_m comes out as. (B_m is same as B)

(Ref. Appendix C)

$$A_m = \begin{bmatrix} -0.5283 & 0 & -0.277 & 0.156 & 0.0296 \\ -35\ 53 & 0 & -54\ 59 & 0 & -0.8217 \\ 0 & 1 & 0 & 0 & 0 \\ -3009\ 2 & 113.2 & -2733.7 & -102.79 & -401.28 \\ -59\ 07 & 0 & 14.48 & 0 & -148.76 \end{bmatrix} \quad (4.10)$$

4.4 1.2 Design of feedback control

A_m can be represented as

$$A_m = \begin{bmatrix} A_{m11} & 0 & A_{m13} & A_{m14} & A_{m15} \\ A_{m21} & A_{m22} & A_{m23} & 0 & A_{m25} \\ 0 & A_{m32} & 0 & 0 & 0 \\ A_{m41} & A_{m42} & A_{m43} & A_{m44} & A_{m45} \\ A_{m51} & 0 & A_{m53} & 0 & A_{m55} \end{bmatrix} \tag{4.11}$$

Let Γ be chosen as

$$\Gamma = \begin{bmatrix} g_1 & 0 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 & 0 \\ 0 & 0 & 0 & g_4 & 0 \\ 0 & 0 & 0 & 0 & g_5 \end{bmatrix} \tag{4.12}$$

Q is chosen to be diagonal, and equal to qI, where $q > 0$ is a real scalar. For the chosen Q, the Lyapunov equation is solved for P Let the second last row of P be $[p_1 \; p_2 \; p_3 \; p_4 \; p_5]$. Then, we study the resulting design, after incorporating the adaptive feedback law given by the equations (4 6), (4.7) and (4.8) by extensive simulation for various operating conditions using the software package SIMNON. The equation for simulation are

Plant :

$$X_1 = A_{11} X_1 + A_{13} X_3 + A_{14} X_4 + A_{15} X_5$$

$$X_2 = A_{21} X_1 + A_{22} X_2 + A_{23} X_3 + A_{25} X_5$$

$$X_3 = A_{32} X_2$$

$$X_4 = A_{41} X_1 + A_{43} X_3 + A_{44} X_4 + A_{45} X_5 + b_5 u$$

$$X_5 = A_{51} X_1 + A_{53} X_3 + A_{55} X_5 \qquad (4.13)$$

Reference Model :

$$X_{m1} = A_{m11} X_{m1} + A_{m13} X_{m3} + A_{m14} X_{m4} + A_{m15} X_{m5}$$

$$X_{m2} = A_{m21} X_{m1} + A_{m22} X_{m2} + A_{m23} X_{m3} + A_{m25} X_{m5}$$

$$X_{m3} = A_{m32} X_{m2}$$

$$X_{m4} = A_{m41} X_1 + A_{m42} X_{m2} + A_{m43} X_{m3} + A_{m44} X_{m4}$$

$$+ A_{m45} X_{m5} + b_5 r$$

$$X_{m5} = A_{m51} X_{m1} + A_{m53} X_{m3} + A_{m55} X_{m5} \qquad (4.14)$$

Controller .

$$K_1 = T_m g_1 X_1$$

$$K_2 = T_m g_2 X_2$$

$$K_3 = T_m g_3 X_3$$

$$K_4 = \Gamma_m g_4 X_4$$

$$K_5 = T_m g_5 X_5$$

Here $T_m = - b_4[p_1(X_1 - X_{m1}) + p_2(X_2 - X_{m2})$

$$+ p_3(X_3 - X_{m3}) + p_4(X_4 - X_{m4}) + p_5(X_5 - X_{m5})]$$

$$u = K_1X_1 + K_2X_2 + K_3X_3 + K_4X_4 + K_5X_5 + r \qquad (4.15)$$

By experimentation we find $q = 10^{-3}$ and $\Gamma = I$ give good stable response.

4 4.1.3 Design of observers

Since all the states are not available, observers are designed for reconstructing the unavailable states. Since plant parameter matrices are not known beforehand (as they vary with different operating conditions reference model matrices are used. Output matrix at design point is considered a constant matrix for design of observers.

4.4 1 3 1 Fourth order observer for $\Delta\omega$ input PSS:

Since $\Delta\omega$ is one of the state variables a fourth order observer will suffice to determine other states. The equations of controller and observer are derived in Appendix D

Controller:

$$u = K_1\hat{X}_1 + K_2X_2 + K_3\hat{X}_3 + K_4\hat{X}_4 + K_5\hat{X}_5 + r$$

$$K_1 = T_m\, g_1\, \hat{X}_1$$

$$K_2 = T_m\, g_2\, X_2$$

$$K_3 = T_m\, g_3\, \hat{X}_3$$

$$K_4 = T_m\, g_4\, \hat{X}_4$$

$$K_5 = T_m\, g_5\, \hat{X}_5$$

$$T_m = -\, b_4 [p_1(\hat{X}_1 - X_{m1}) + p_2(X_2 - X_{m2})$$

$$+ p_3(\hat{X}_3 - X_{m3}) + p_4(\hat{X}_4 - X_{m4}) + p_5(\hat{X}_5 - X_{m5})]$$

(4.16)

Observer

$$z_1 = B_{11}z_1 + B_{12}z_2 + B_{13}z_3 + B_{14}z_4 + (C_1 - D_1)X_2$$

$$z_2 = B_{21}z_2 + B_{22}z_2 + B_{23}z_3 + B_{24}z_4 + (C_2 - D_2)X_2$$

$$z_3 = B_{31}z_1 + B_{32}z_2 + B_{33}z_3 + B_{34}z_4 + (C_3 - D_3)X_2$$

$$z_4 = B_{41}z_1 + B_{42}z_2 + B_{43}z_3 + B_{44}z_4 + (C_4 - D_4)X_2$$

$$\hat{X}_1 = z_1 - m_1X_2$$

$$\hat{X}_3 = z_3 - m_3X_2$$

$$\hat{X}_4 = z_4 - m_4 X_2$$

$$\hat{X}_5 = z_5 - m_5 X_2 \qquad (4.17)$$

Parameters B_{11} . .. . B_{44}, C_1 . ....C_4 and D_1 .. D_4 are defined in Appendix D.

4.4 1 3.2 Fifth order observer for ΔPe input PSS.

For fifth order observer design we take parameter matrices A_m and B_m of reference model and output matrix C_m at the design point. The equations for observer and controller are :-

Controller :

$$u = K_1\hat{X}_1 + K_2\hat{X}_2 + K_3\hat{X}_3 + K_4\hat{X}_4 + K_5\hat{X}_5 + r$$

$$K_1 = T_m\, g_1\, \hat{X}_1$$

$$K_2 = T_m\, g_2\, \hat{X}_2$$

$$K_3 = T_m\, g_3\, \hat{X}_3$$

$$K_4 = T_m\, g_4\, \hat{X}_4$$

$$K_5 = T_m\, g_5\, \hat{X}_5$$

$$T_m = - b_4[p_1(\hat{X}_1 - X_{m1}) + p_2(\hat{X}_2 - X_{m2})$$

$$+ p_3(\hat{X}_3 - X_{m3}) + p_4(\hat{X}_4 - X_{m4}) + p_5(\hat{X}_5 - X_{m5})]$$

(4.18)

Observer :

$$\hat{X}_1 = B_{11}\hat{X}_1 + B_{12}\hat{X}_2 + B_{13}\hat{X}_3 + B_{14}\hat{X}_4 + B_{15}\hat{X}_5 - m_1 y$$

$$\hat{X}_2 = B_{21}\hat{X}_1 + B_{22}\hat{X}_2 + B_{23}\hat{X}_3 + B_{24}\hat{X}_4 + B_{25}\hat{X}_5 - m_2 y$$

$$\hat{X}_3 = B_{31}\hat{X}_1 + B_{32}\hat{X}_2 + B_{33}\hat{X}_3 + B_{34}\hat{X}_4 + B_{35}\hat{X}_5 - m_3 y$$

$$\hat{X}_4 = B_{41}\hat{X}_1 + B_{42}\hat{X}_2 + B_{43}\hat{X}_3 + B_{44}\hat{X}_4 + B_{45}\hat{X}_5 + b_4 u - m_4 y$$

$$\hat{X}_5 = B_{51}\hat{X}_1 + B_{52}\hat{X}_2 + B_{53}\hat{X}_3 + B_{54}\hat{X}_4 + B_{55}\hat{X}_5 - m_5 y \tag{4.19}$$

Where $B_1 . \; . \; .B_{55}$ are defined in Appendix E.

4.4.2 MRASVC stabilizer design

4.4.2.1 Selection of Reference Model.

Reference Model is selected in a similar way as in MRAPSS design The closed loop poles are located at the same locations as in case of PSS design.

B is given as [0 0 0 0 1000].

Using it A_m comes out as (for problem under consideration) (Ref. Appendix C)

$$A_m = \begin{bmatrix} -0\ 5283 & 0 & -0\ 277 & 0.156 & 0.0296 \\ -35.53 & 0 & -54.59 & 0 & -0.8217 \\ 0 & 1 & 0 & 0 & 0 \\ -1212\ 1 & 0 & -9\ 64 & -100 & -408.98 \\ 601\ 48 & 7\ 1123 & 1112.5 & 1.0513 & -151.55 \end{bmatrix}$$

(4.20)

4.4.2 2 Design of feedback control

A_m can be represented as

$$A_m = \begin{bmatrix} A_{m11} & 0 & A_{m13} & A_{m14} & A_{m15} \\ A_{m21} & A_{m22} & A_{m23} & 0 & A_{m25} \\ 0 & A_{m32} & 0 & 0 & 0 \\ A_{m41} & 0 & A_{m43} & A_{m44} & A_{m45} \\ A_{m51} & A_{m52} & A_{m53} & 0 & A_{m55} \end{bmatrix} \qquad (4\ 21)$$

Proceeding on similar lines as in section 4.4.1.2 we can get the simulation equations :

Plant

$$\dot{X}_1 = A_{11} X_1 + A_{13} X_3 + A_{14} X_4 + A_{15} X_5$$

$$X_2 = A_{21} X_1 + A_{22} X_2 + A_{23} X_3 + A_{25} X_5$$

$$X_3 = A_{32} X_2$$

$$X_4 = A_{41} X_1 + A_{43} X_3 + A_{44} X_4 + A_{45} X_5$$

$$X_5 = A_{51} X_1 + A_{53} X_3 + A_{55} X_5 + b_5 u$$

$$(4.22)$$

Reference Model :

$$X_{m1} = A_{m11} X_{m1} + A_{m13} X_{m3} + A_{m14} X_{m4} + A_{m15} X_{m5}$$

$$X_{m2} = A_{m21} X_{m1} + A_{m22} X_{m2} + A_{m23} X_{m3} + A_{m25} X_{m5}$$

$$X_{m3} = A_{m32} X_{m2}$$

$$X_{m4} = A_{m41} X_1 + A_{m42} X_{m2} + A_{m43} X_{m3} + A_{m44} X_{m4} + A_{m45} X_{m5} + b_5 r$$

$$X_{m5} = A_{m51} X_{m1} + A_{m53} X_{m3} + A_{m55} X_{m5} \; b_5 r$$

$$(4.23)$$

4.4 2 3 Design of observers

Full order observer is required since both Δp_m and ΔQ_m are not the directly available states in state space model. The basic nature of equations remains the same for both signals, only the parameters are different Controller and observer equations are given below .

Controller ·

$$u = K_1\hat{X}_1 + K_2\hat{X}_2 + K_3\hat{X}_3 + K_4\hat{X}_4 + K_5\hat{X}_5 + r$$

$$K_1 = T_m \, g_1 \, \hat{X}_1$$

$$K_2 = T_m \, g_2 \, \hat{X}_2$$

$$K_3 = T_m \, g_3 \, \hat{X}_3$$

$$K_4 = T_m \, g_4 \, \hat{X}_4$$

$$K_5 = T_m \, g_5 \, \hat{X}_5$$

$$T_m = - b_4[p_1(\hat{X}_1 - X_{m1}) + p_2(\hat{X}_2 - X_{m2})$$

$$+ p_3(\hat{X}_3 - X_{m3}) + p_4(\hat{X}_4 - X_{m4}) + p_5(\hat{X}_5 - X_{m5})] \qquad (4.24)$$

Observer :

$$\hat{X}_1 = Q_{11}\hat{X}_1 + Q_{12}\hat{X}_2 + Q_{13}\hat{X}_3 + Q_{14}\hat{X}_4 + Q_{15}\hat{X}_5 - m_1 y$$

$$\dot{\hat{X}}_2 = Q_{21}\hat{X}_1 + Q_{22}\hat{X}_2 + Q_{23}\hat{X}_3 + Q_{24}\hat{X}_4 + Q_{25}\hat{X}_5 - m_2 y$$

$$\hat{X}_3 = Q_{31}\hat{X}_1 + Q_{32}\hat{X}_2 + Q_{33}\hat{X}_3 + Q_{34}\hat{X}_4 + Q_{35}\hat{X}_5 - m_3 y$$

$$\hat{X}_4 = Q_{41}\hat{X}_1 + Q_{42}\hat{X}_2 + Q_{43}\hat{X}_3 + Q_{44}\hat{X}_4 + Q_{45}\hat{X}_5 - m_4 y$$

$$\hat{X}_5 = Q_{51}\hat{X}_1 + Q_{52}\hat{X}_2 + Q_{53}\hat{X}_3 + Q_{54}\hat{X}_4 + Q_{55}\hat{X}_5 + b_5 u - m_5 y$$

$$(4.25)$$

Where $Q_{11} \, .. \, .Q_{55}$ are defined in Appendix E.

4 4.3 Simultaneous Operation of Stabilizers

Another aspect of Modern controls gaining momentum is simultaneous operation of controllers Four such combinations are possible for controls designed in this chapter :-

(i) ΔPe input PSS and ΔP_m input SVC stabilizer.

(ii) $\Delta\omega$ input PSS and ΔQ_m input SVC stabilizer.

(iii) ΔPe input PSS and ΔQ_m input SVC stabilizer.

(iv) $\Delta\omega$ input PSS and ΔP_m input SVC stabilizer.

4 5 OBSERVATIONS

Model reference adaptive controllers were designed and tested using software package SIMNON. Simulation results are presented in Fig 4.2 to 4.7 as follows:

Fig. 4 2 (a), 4 2 (b), 4 2 (c) - $\Delta\omega$ input PSS for different operating conditions.

Fig 4 3 (a), 4 3 (b), 4 3 (c) - ΔP_e input PSS for different operating conditions.

Fig 4.4 (a), 4.4 (b), 4.4 (c) - ΔP_m input SVC Stabilizer for different operating conditions.

Fig. 4 5 (a), 4.5 (b), 4 5 (c) - ΔQ_m input SVC Stabilizer for different operating conditions

Fig. 4 6 (a), 4 6 (b), 4 6 (c) - $\Delta\omega$ input PSS and ΔP_m input SVC Stabilizer operating simultaneously

Fig. 4 7 (a), 4 7 (b), 4 7 (c) - $\Delta\omega$ input PSS and ΔQ_m input

SVC Stabilizer operating simultaneously.

It is observed from above mentioned figures that the best operation of controllers or their simultaneous operation is obtained near design point for small variations from it. It is also found that simultaneous operation is not always improving performance of the system as compared to single controller operation ΔP_e input PSS and ΔQ_m (or ΔP_m) input SVC Stabilizer combinations in fact do not improve the system performance at all and oscillations are present even after a long time.

4 6 CONCLUDING REMARKS

In this chapter Model reference adaptive stabilizers have been designed. While $\Delta\omega$ and ΔPe are input signals for PSS design, ΔP_m and ΔQ_m are input signals for SVC stabilizer design. simultaneous operation of stabilizers has also been discussed.

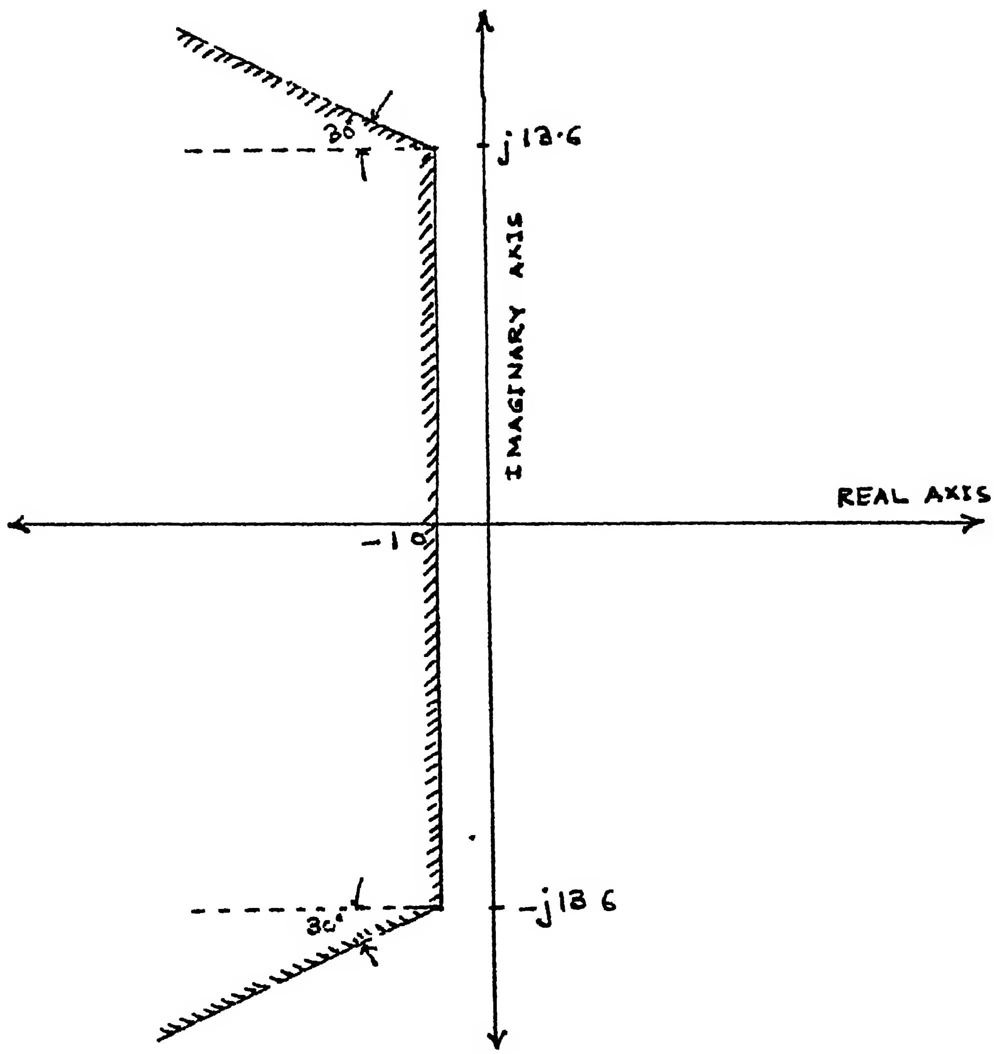


FIG. 4.1: SECTOR INDICATING THE PERMISSIBLE LOCATION OF CLOSED LOOP EIGENVALUES.

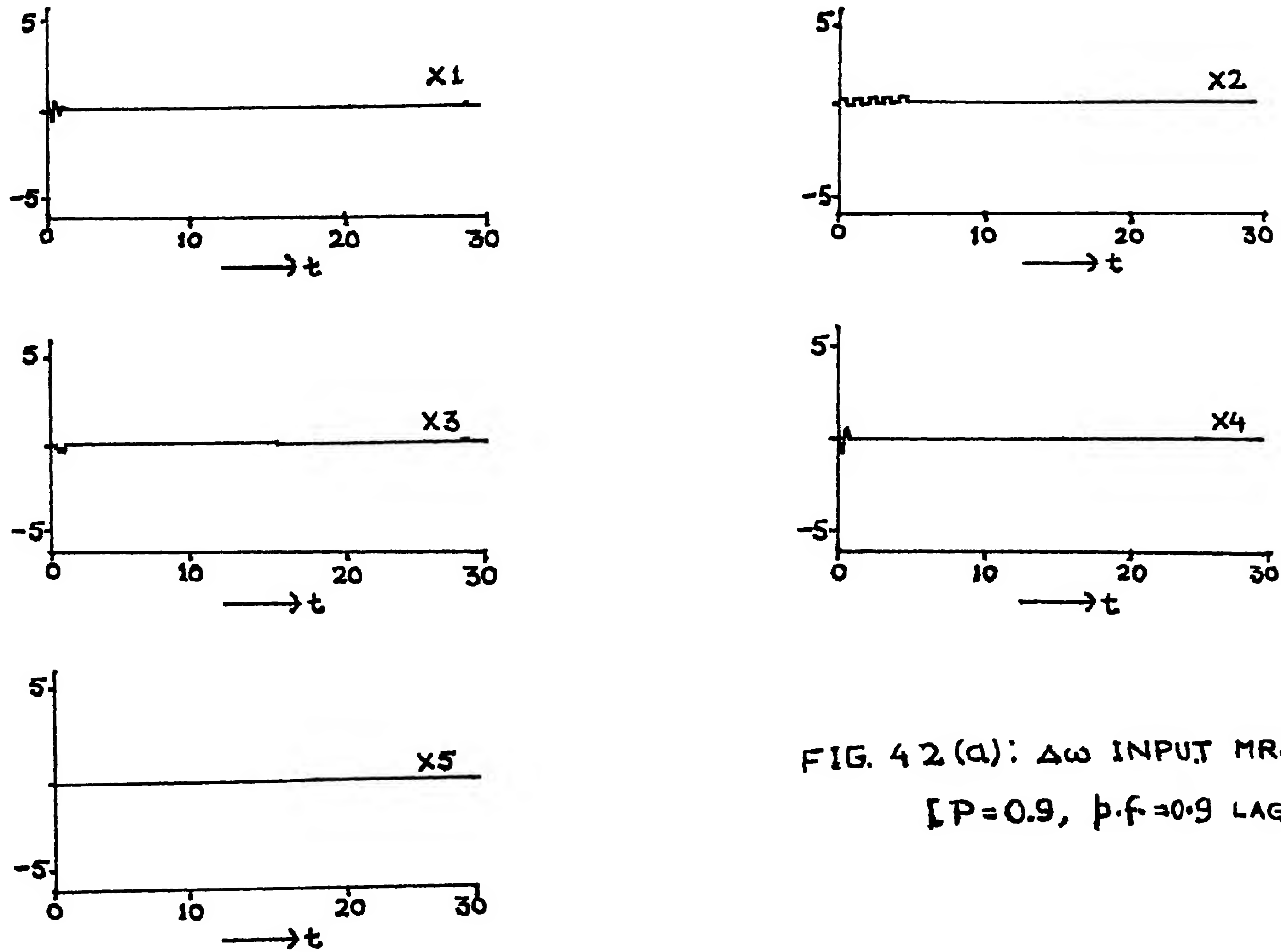


FIG. 4.2 (a): $\Delta\omega$ INPUT MRAPSS RESPONSE
[P = 0.9, p.f = 0.9 LAG]

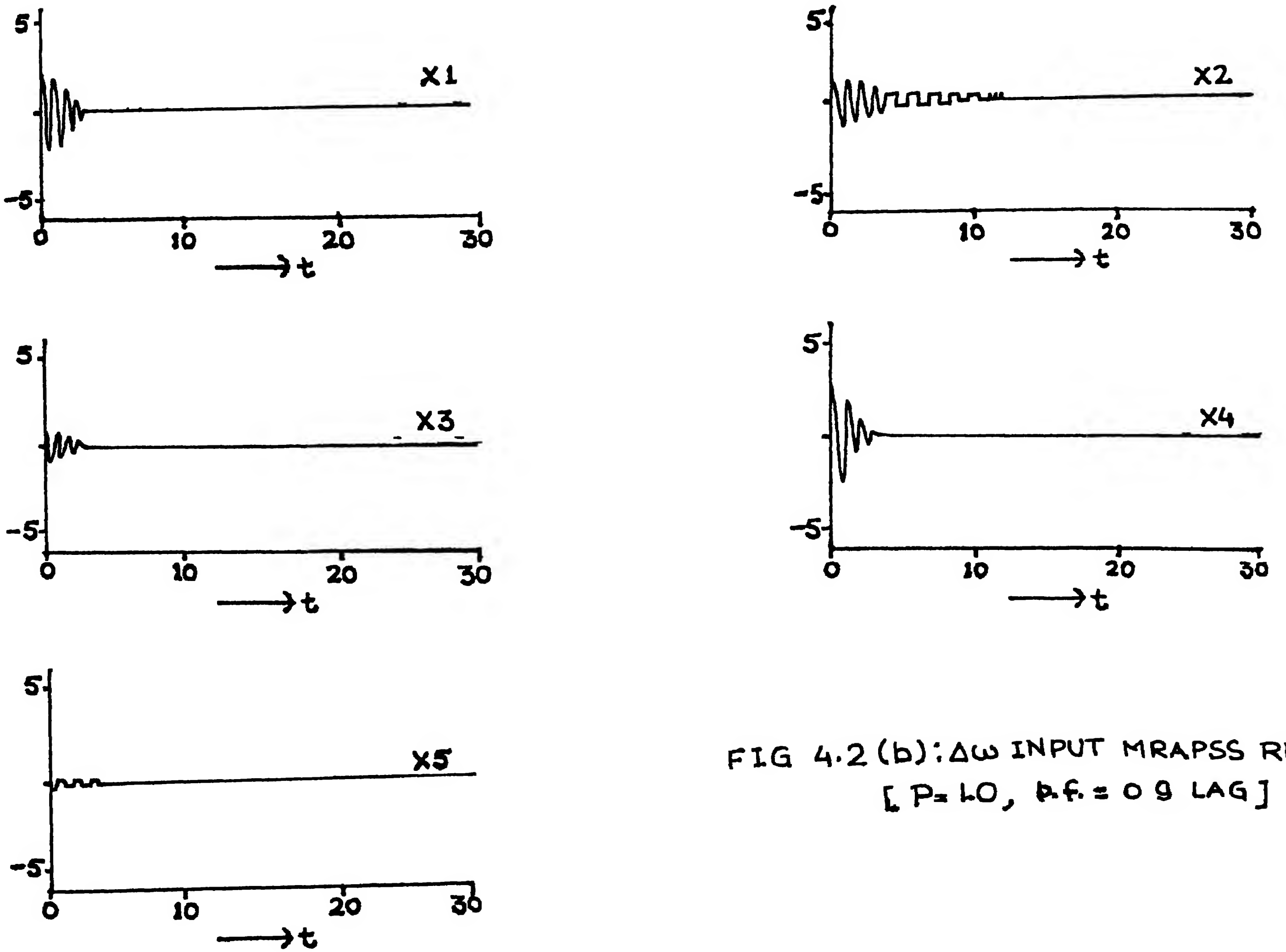


FIG 4.2 (b): Δω INPUT MRAPSS RESPONSE
[P= 1.0, p.f. = 0.9 LAG]

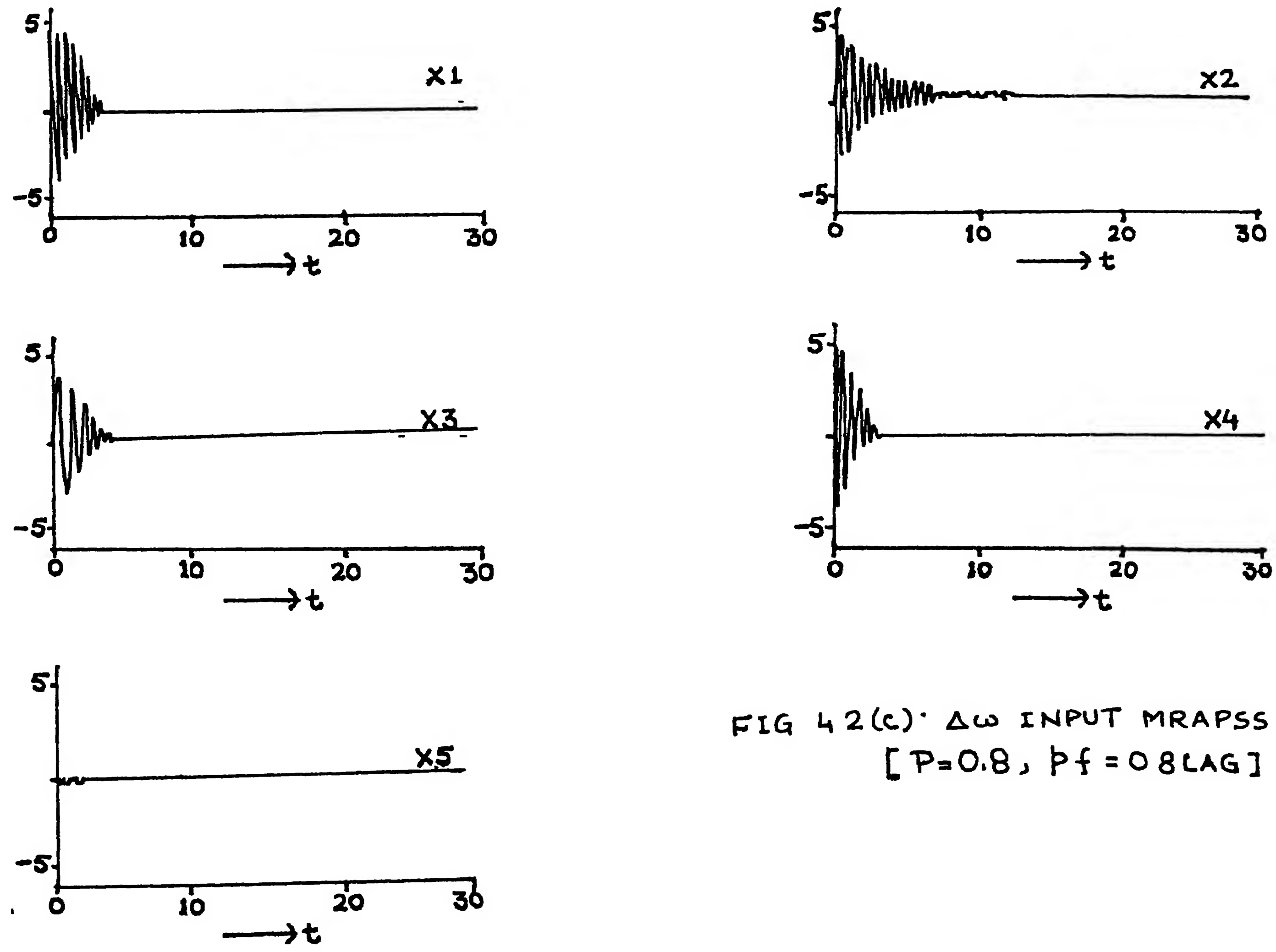


FIG 4 2(c)· Δω INPUT MRAPSS RESPONSE
[P=0.8 , pf = 0 8LAG]

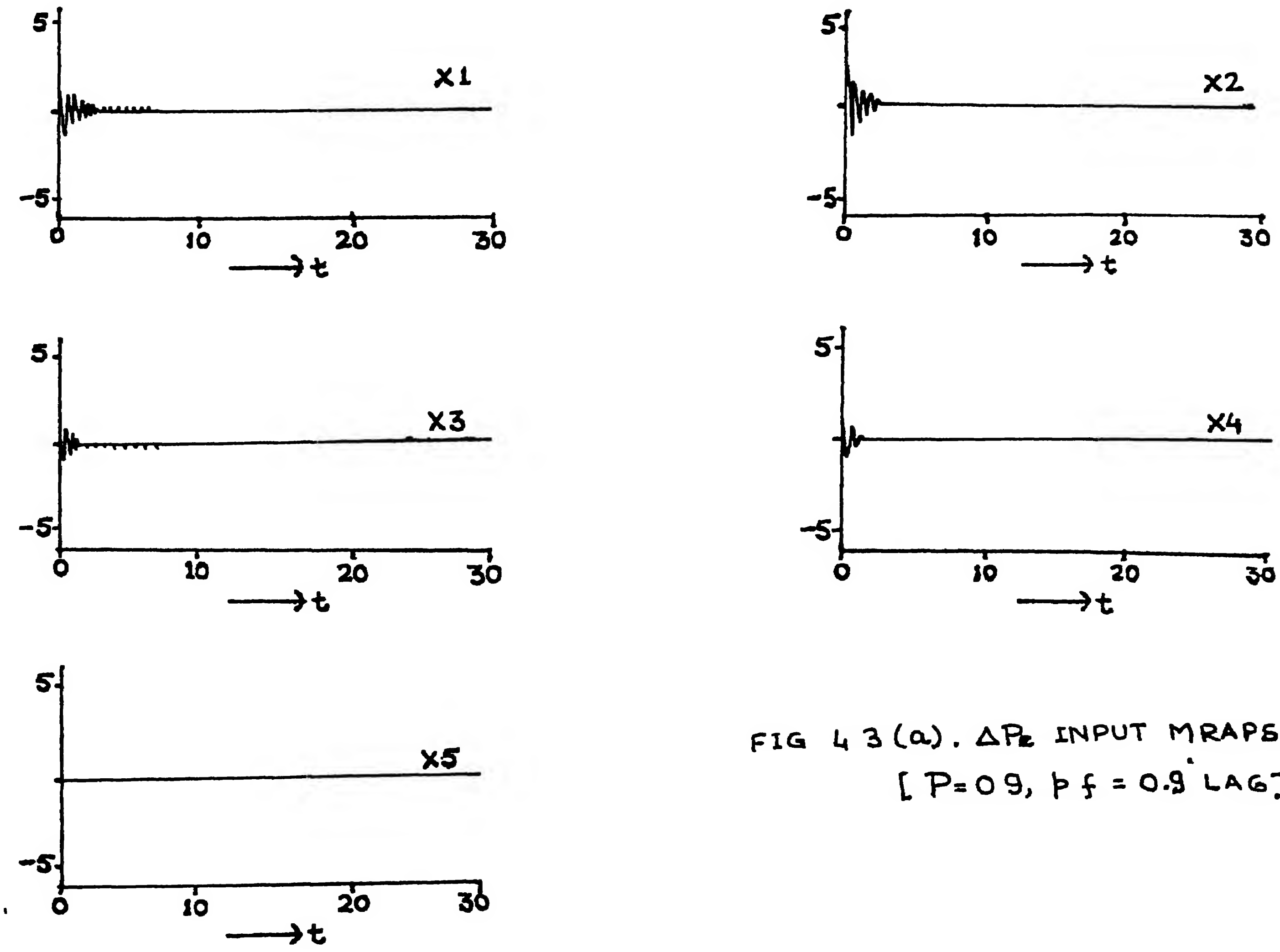


FIG 4 3 (a). ΔP_e INPUT MRAPSS RESPONSE
[P = 0.9, pf = 0.9 LAG]

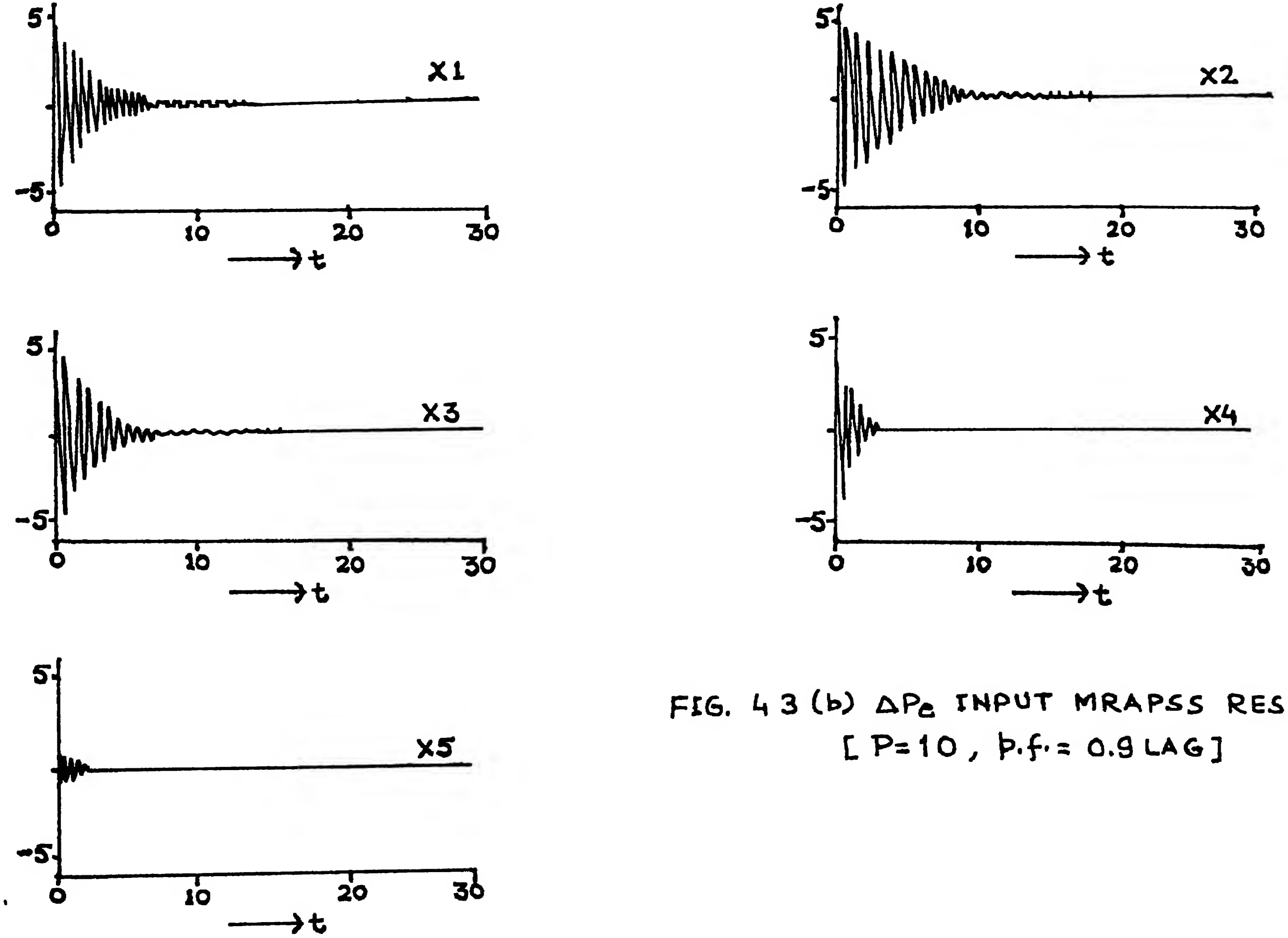


FIG. 4 3 (b) ΔP_e INPUT MRAPSS RESPONSE
[P=10 , p.f.= 0.9 LAG]

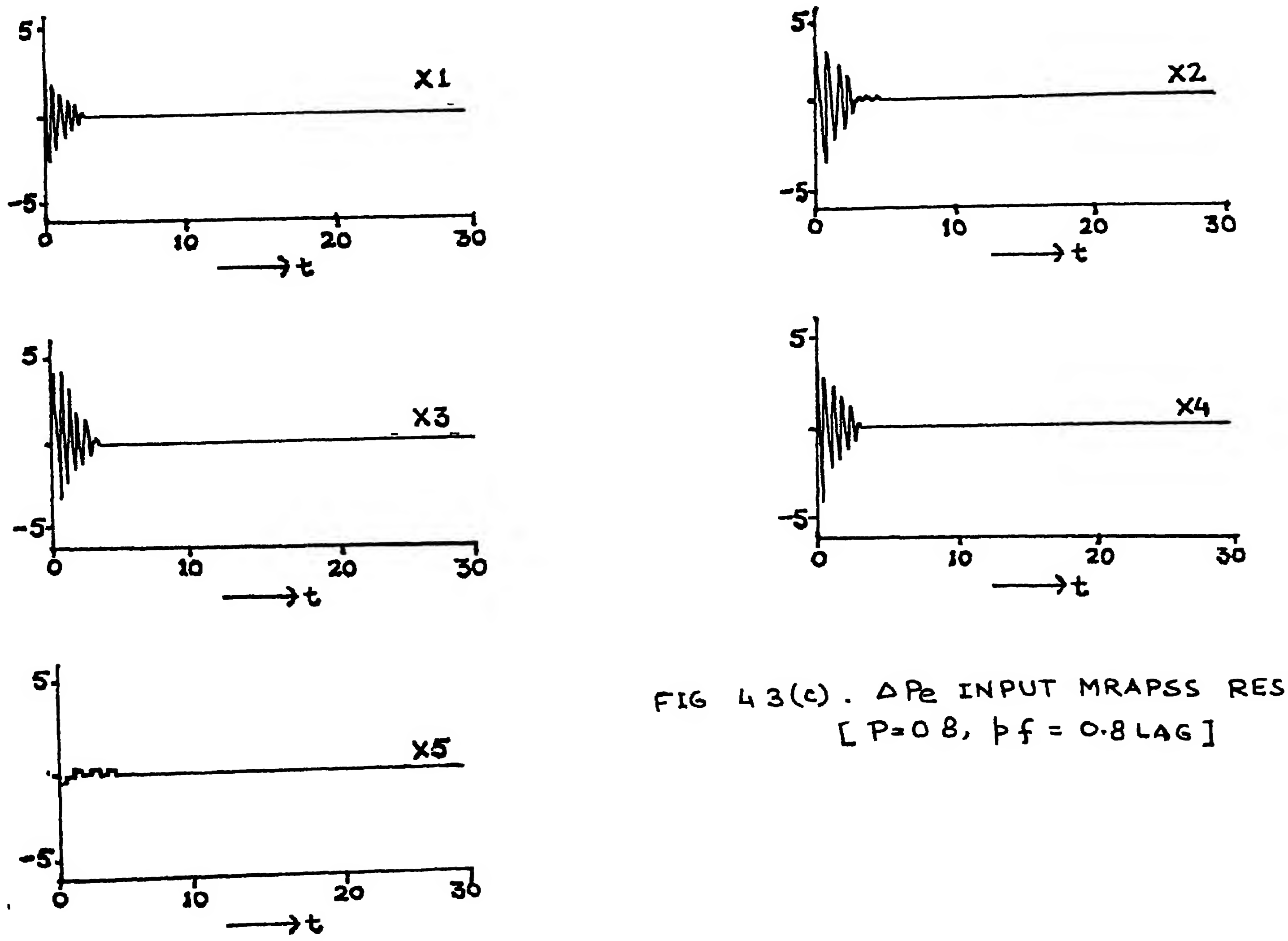
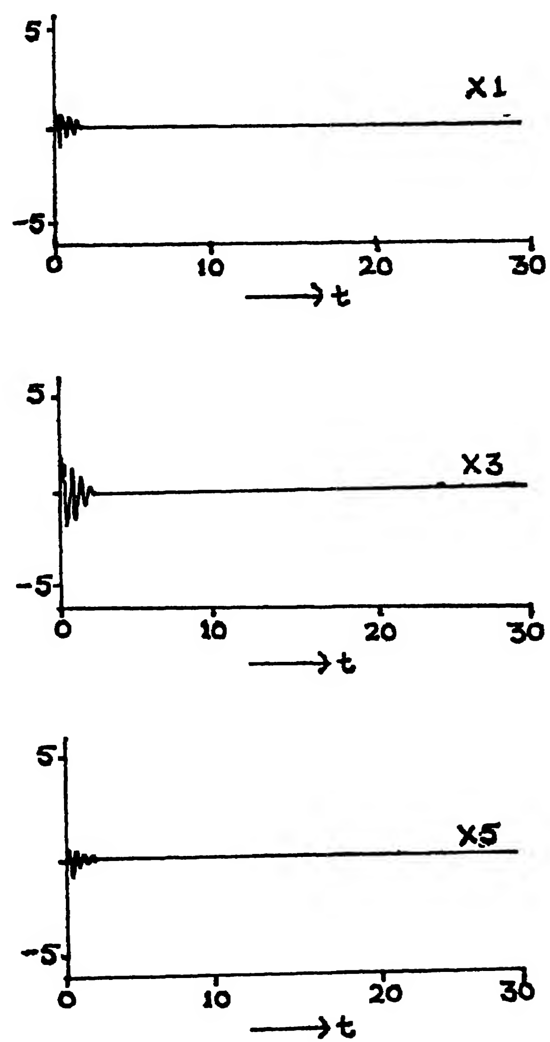


FIG 4.3(c). ΔP_e INPUT MRAPSS RESPONSE
[P = 0.8, pf = 0.8 LAG]



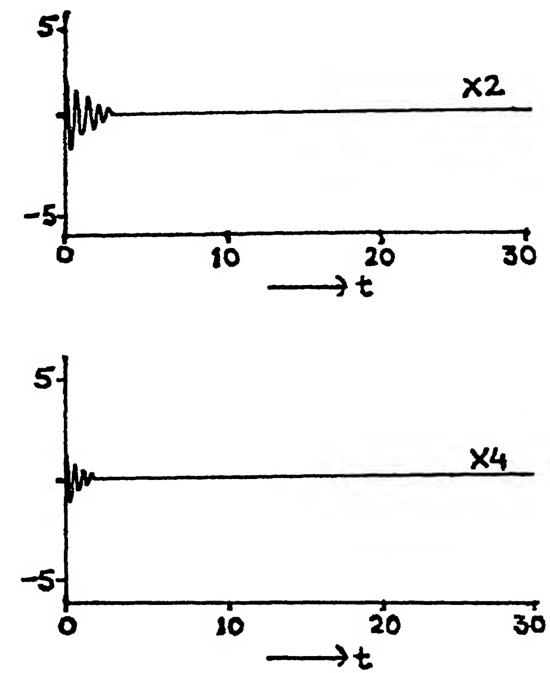


FIG 4 4 (a). ΔP_m INPUT SVC STABILIZER RESPONSE
[P = 0 9, pf = 0 9 LAG]

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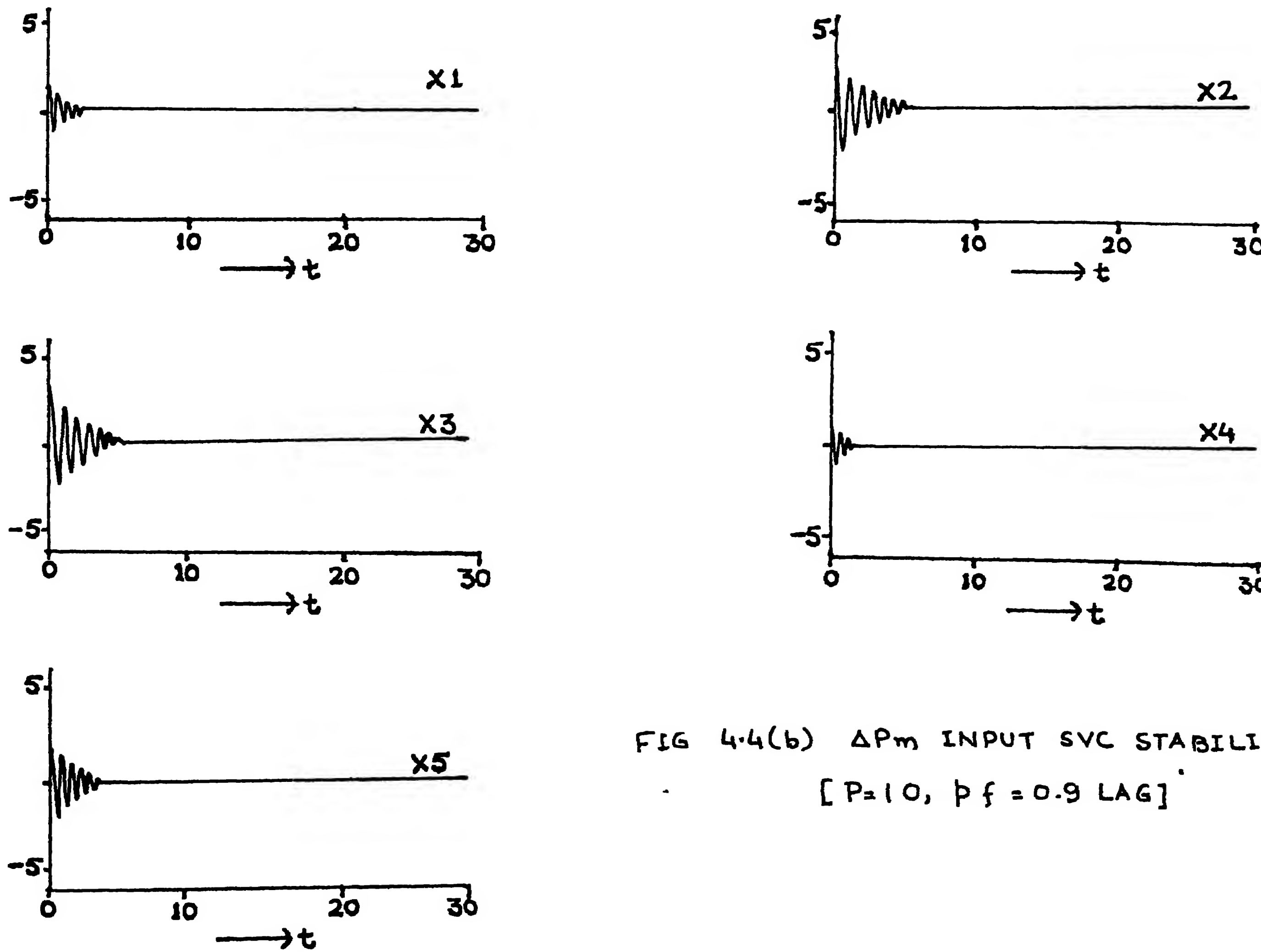


FIG 4.4(b) ΔP_m INPUT SVC STABILIZER RESPONSE
[P=1.0, pf = 0.9 LAG]

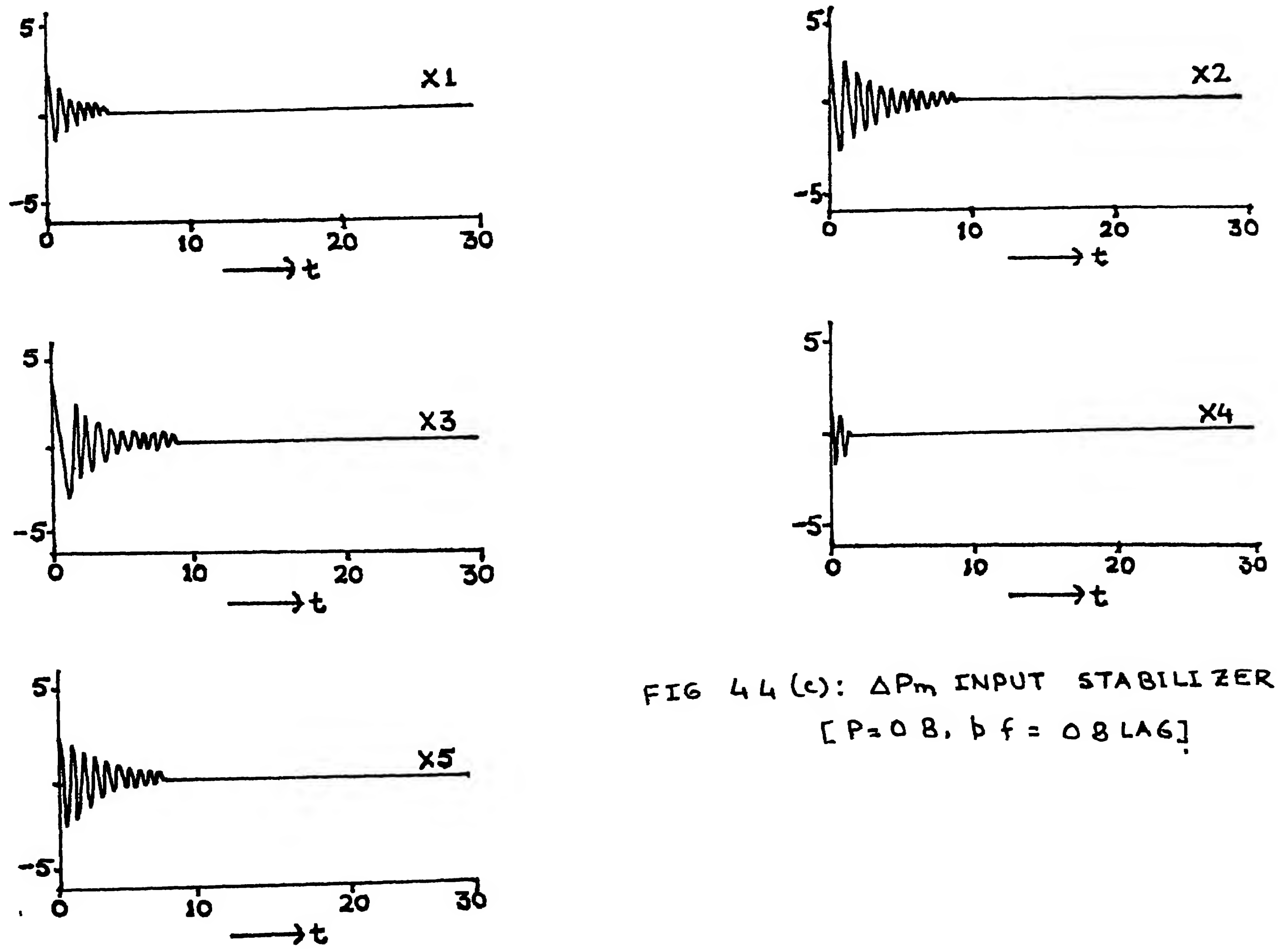
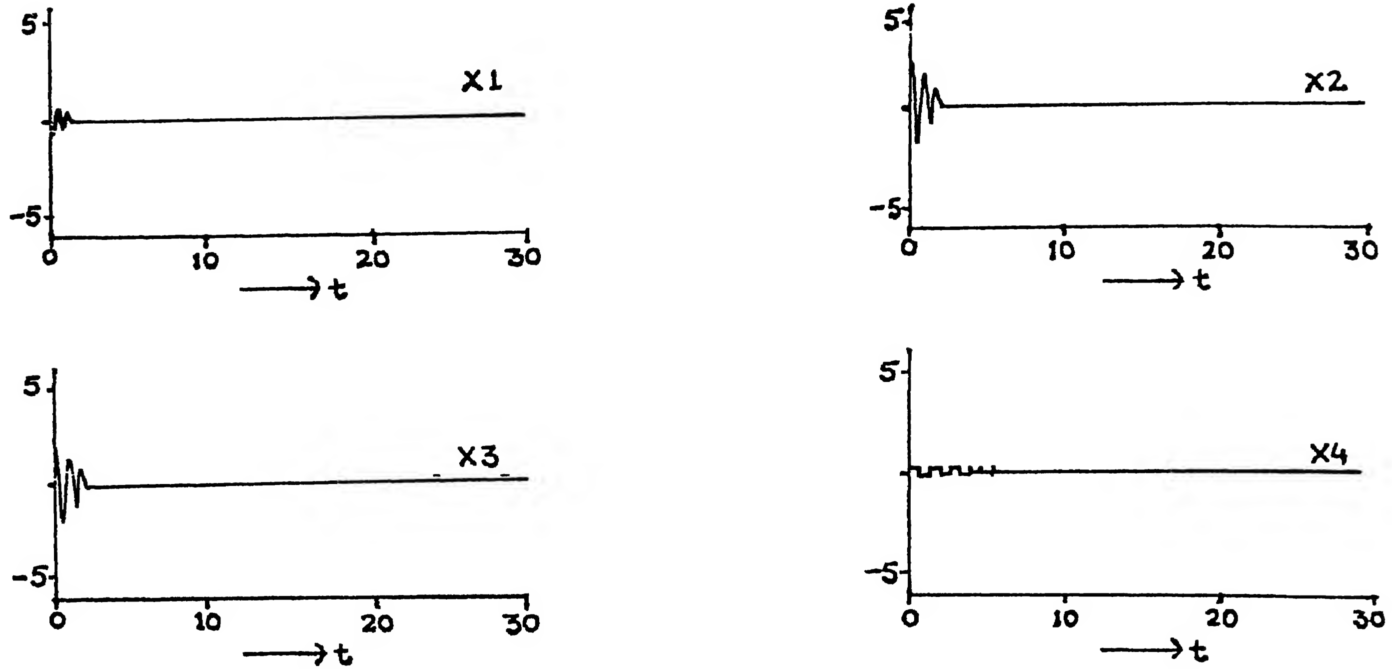


FIG 4 4 (c): ΔP_m INPUT STABILIZER RESPONSE (SVC)
[P=0 8, pf = 0 8 LAG]



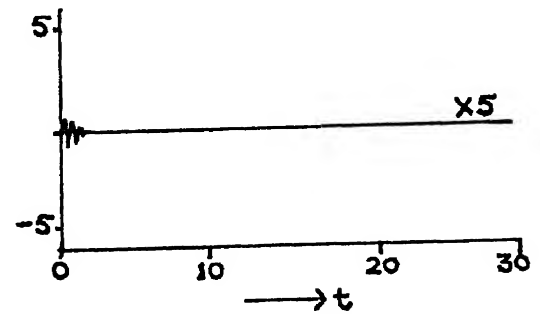


FIG 4 5(a): ΔQ_m INPUT STABILIZER (SVC) RESPONSE
[P = 0 9, p f = 0 9 LAG]

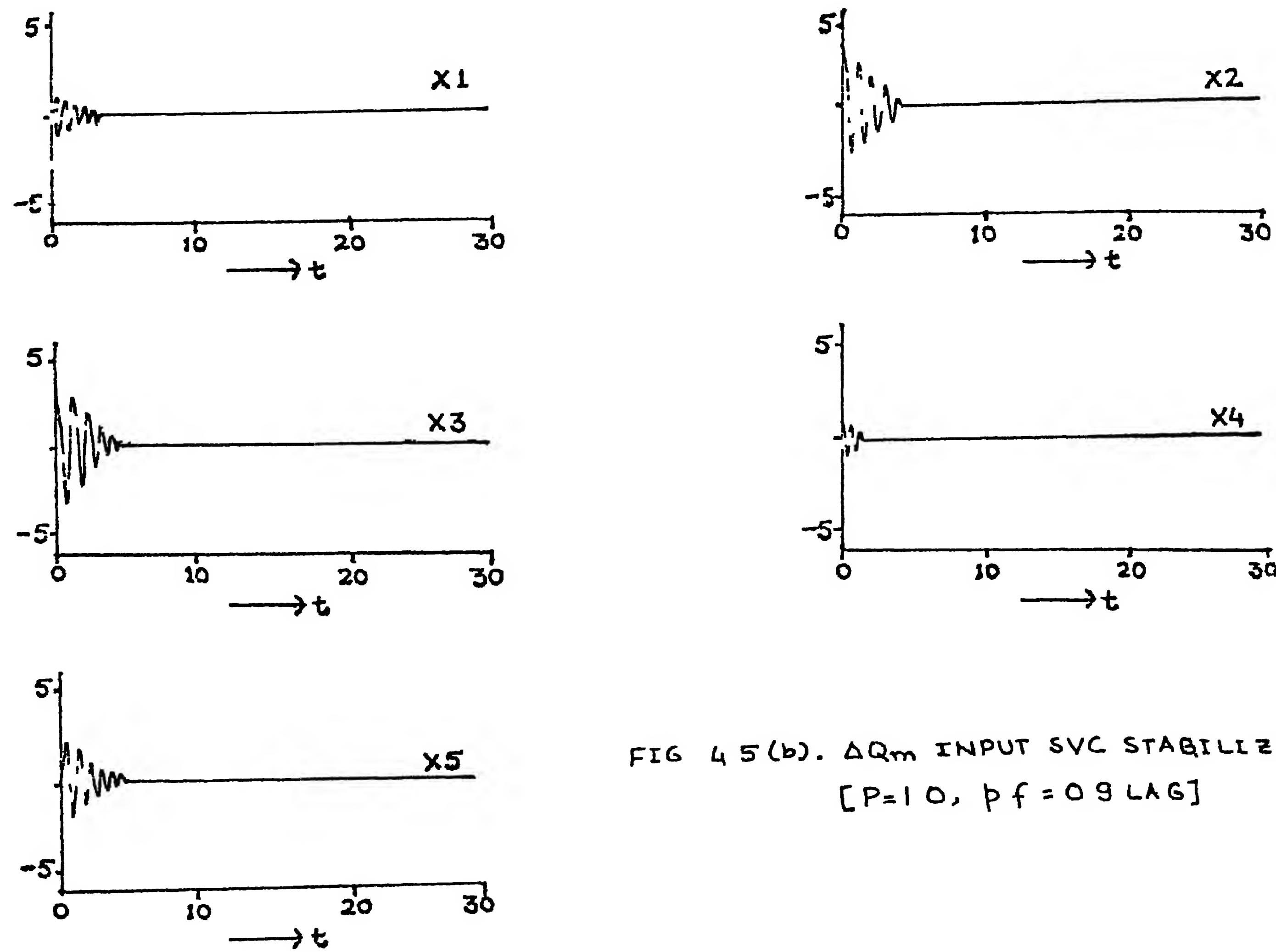


FIG 4 5(b). ΔQ_m INPUT SVC STABILIZER RESPONSE
[P=1 0, pf = 0 9 LAG]

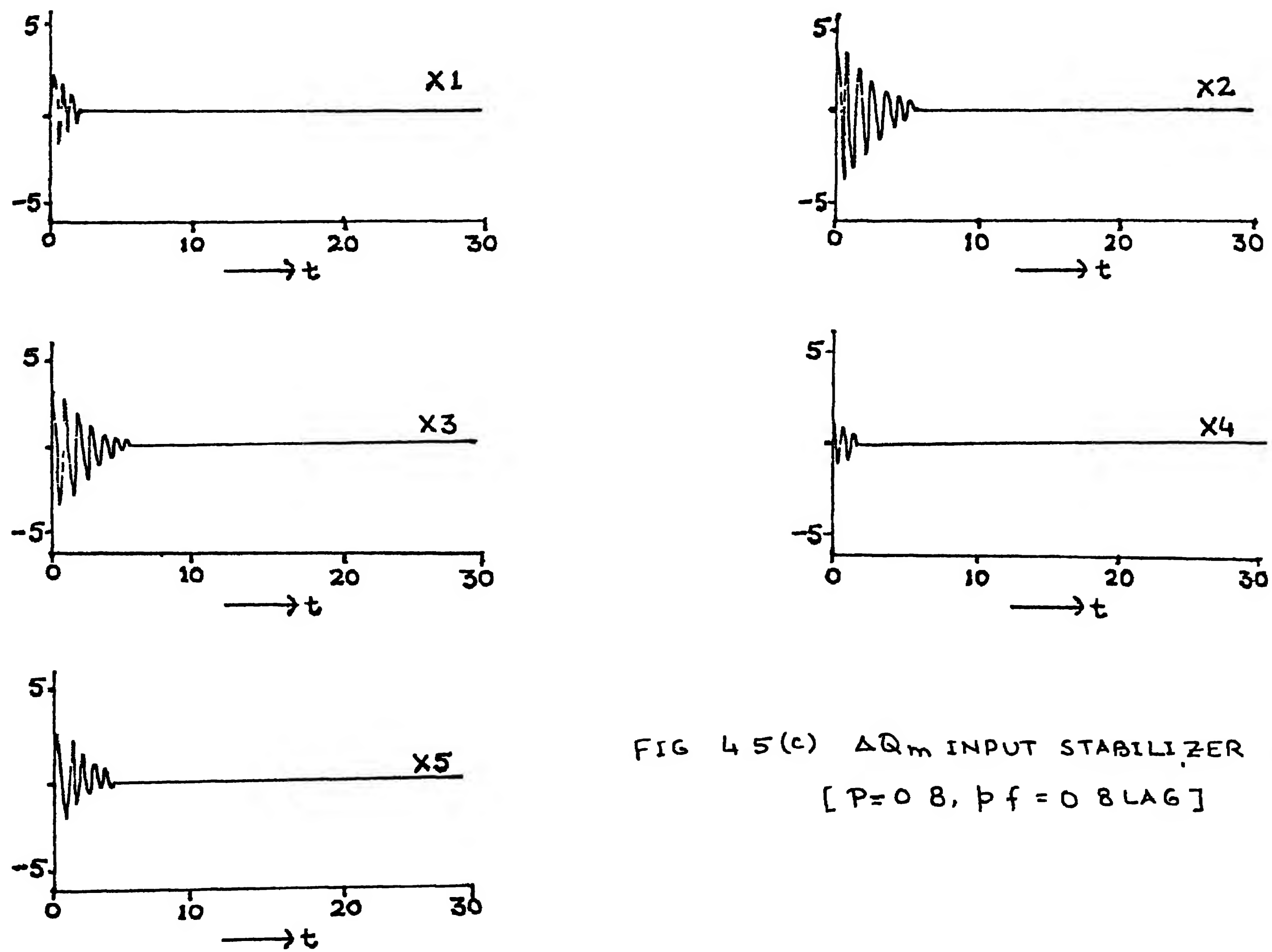


FIG 4 5(c) ΔQ_m INPUT STABILIZER RESPONSE

[P=0 8, pf = 0 8 LAG]

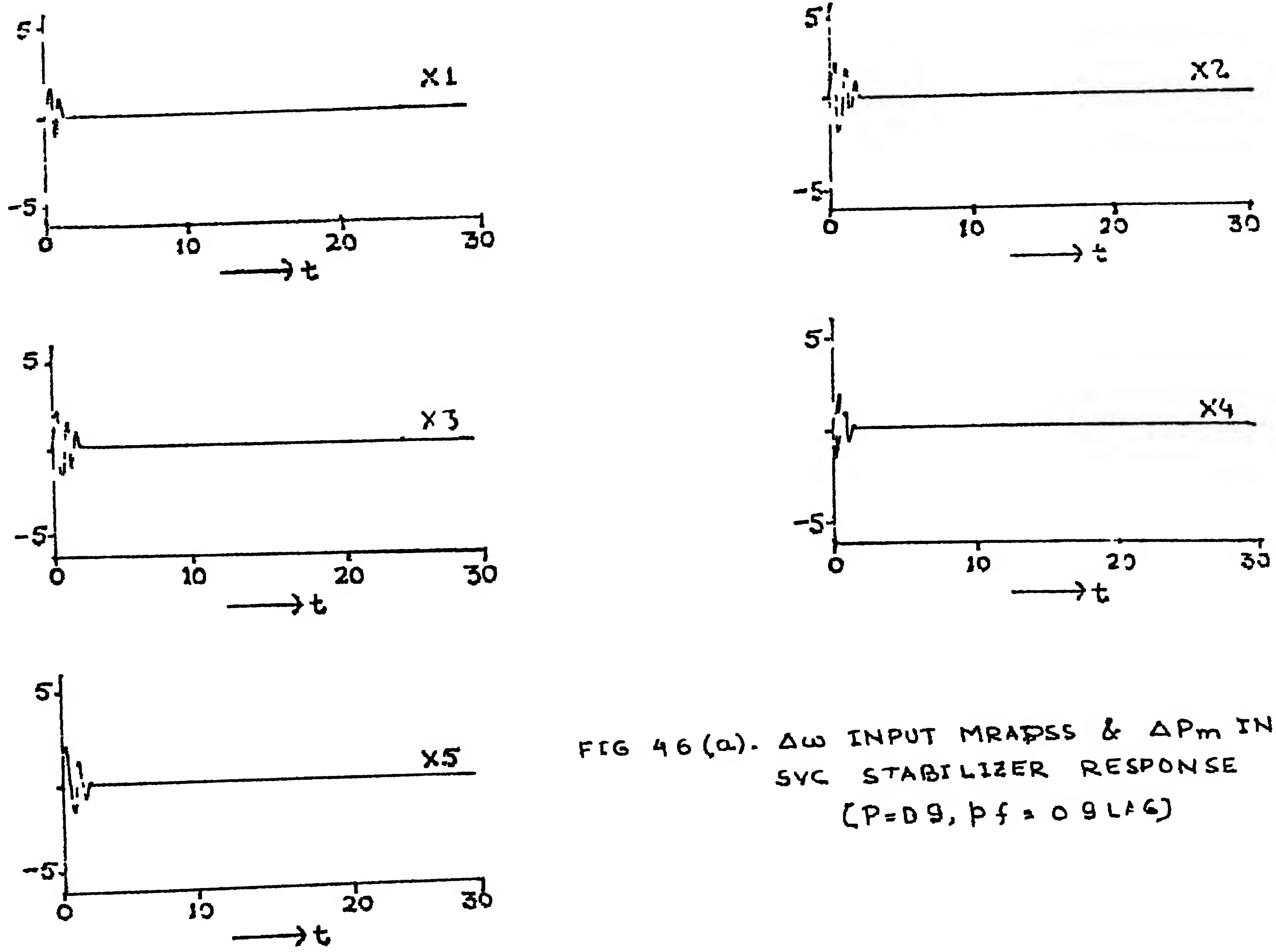
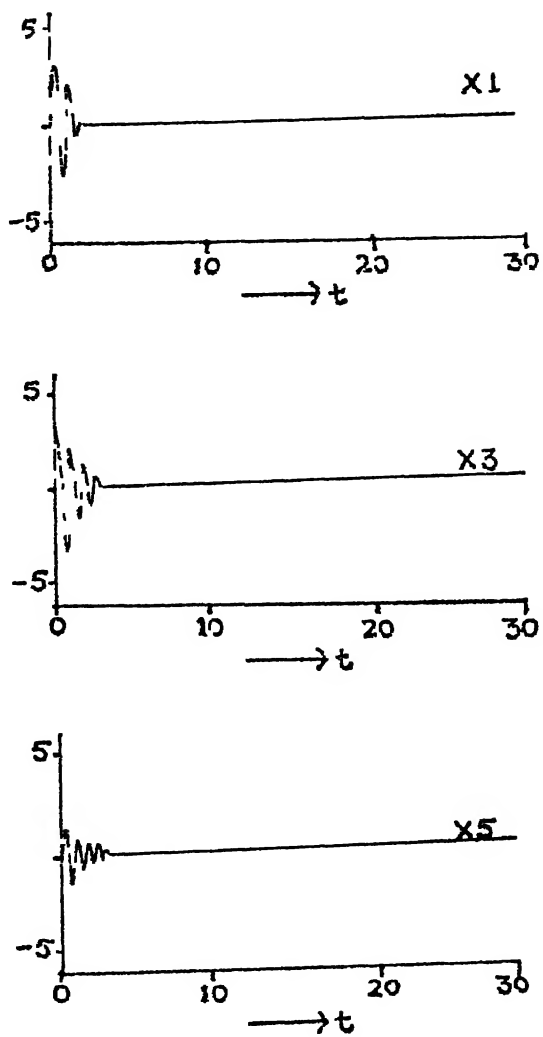


FIG 4.6 (a). $\Delta\omega$ INPUT MRAPSS & ΔP_m INPUT SVC STABILIZER RESPONSE (P=0.9, pf = 0.9 LAG)



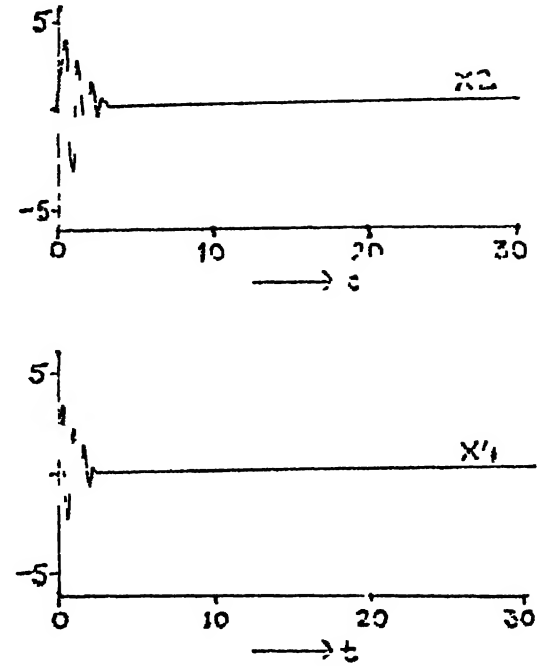


FIG 4 6(b)· $\Delta\omega$ INPUT MRAPSS AND ΔP_m INPUT
SVC STABILIZER RESPONSE
[P=1 0, pf = 0 9 LAG]

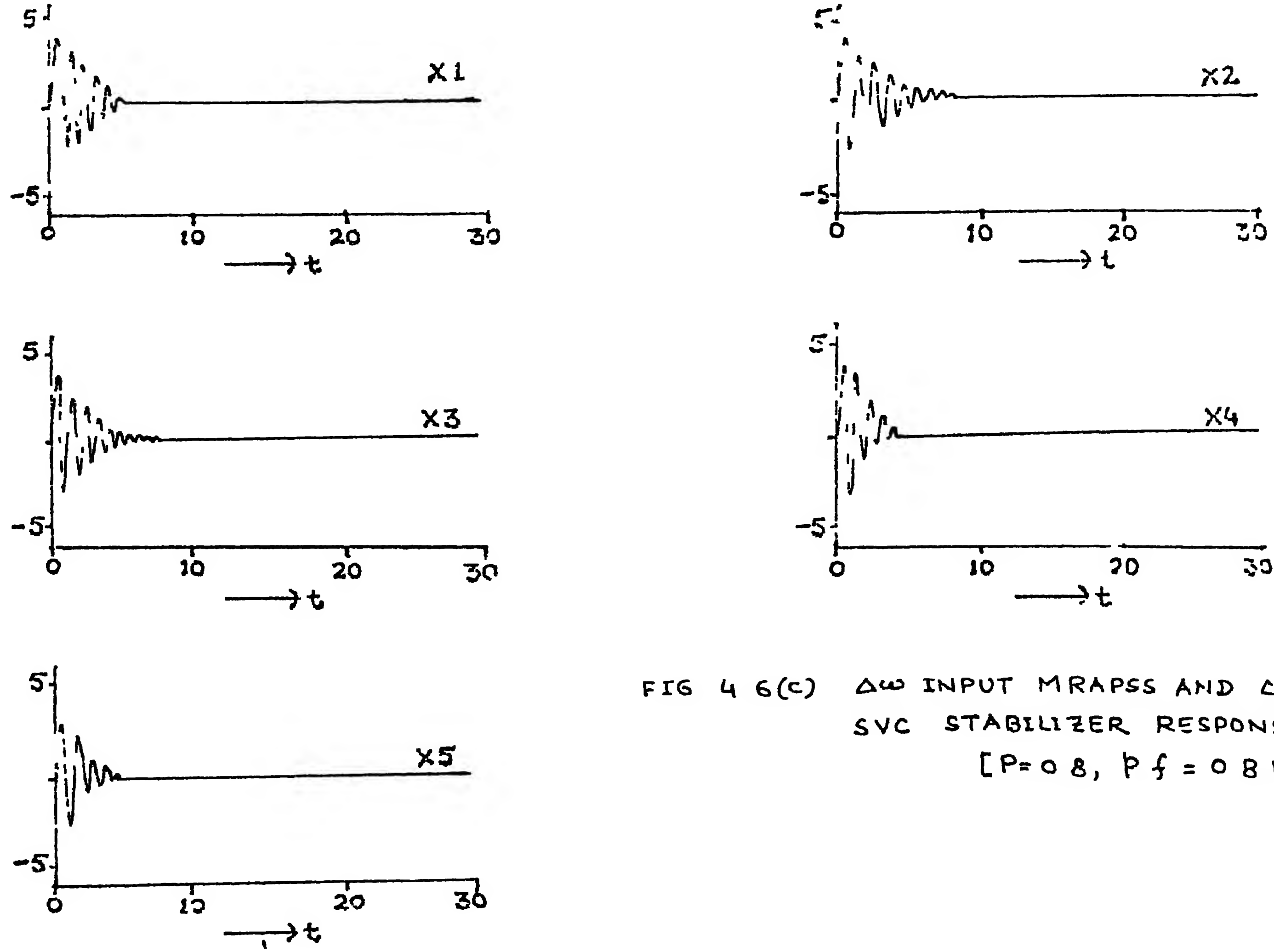


FIG 4 6(c) $\Delta\omega$ INPUT MRAPSS AND ΔP_m INPUT SVC STABILIZER RESPONSE
[P = 0 8, pf = 0 8 LAG]

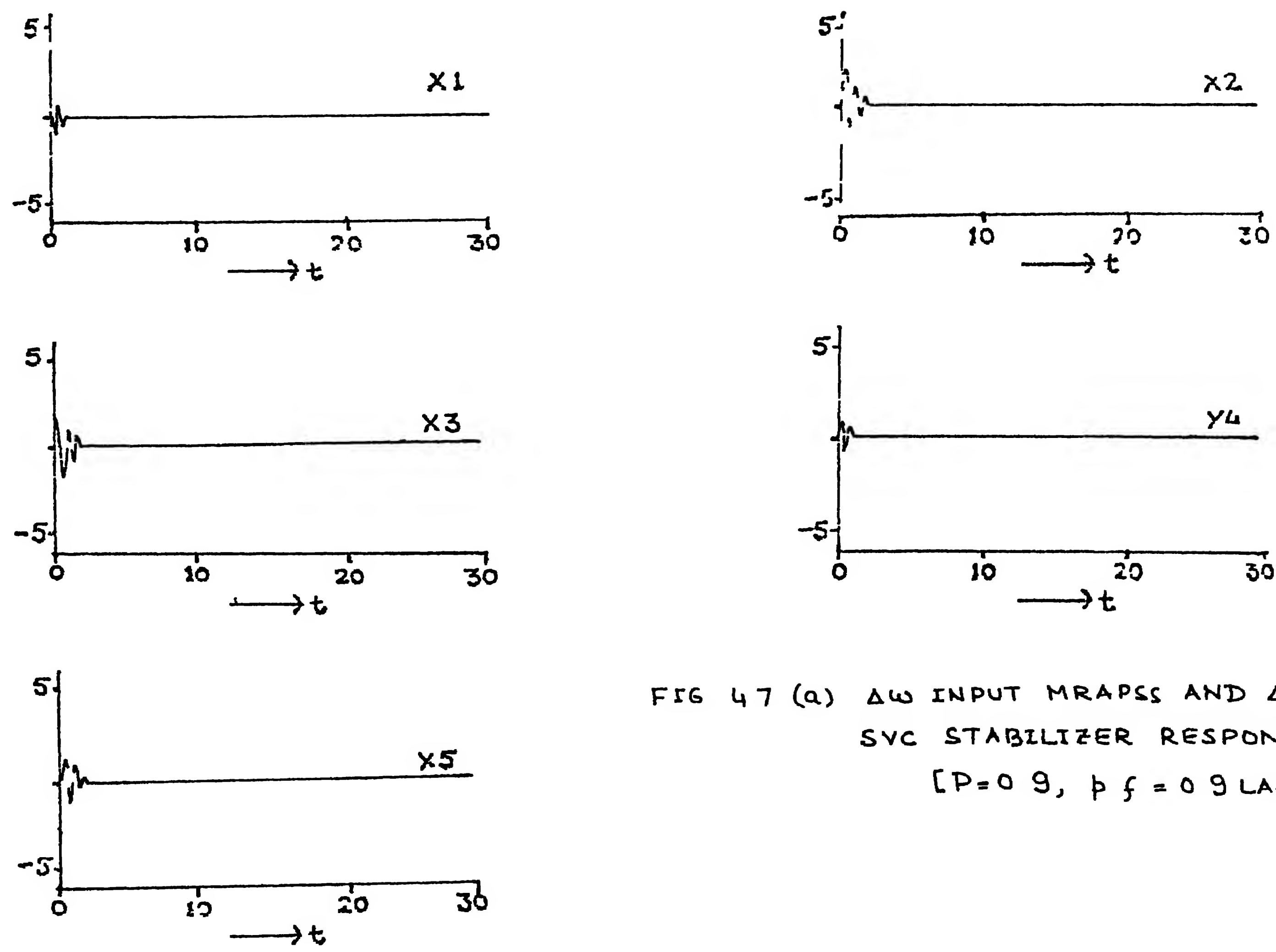


FIG 4 7 (a) $\Delta\omega$ INPUT MRAPSS AND ΔQ_m INPUT SVC STABILIZER RESPONSE [P=0 9, p f = 0 9 LAG]

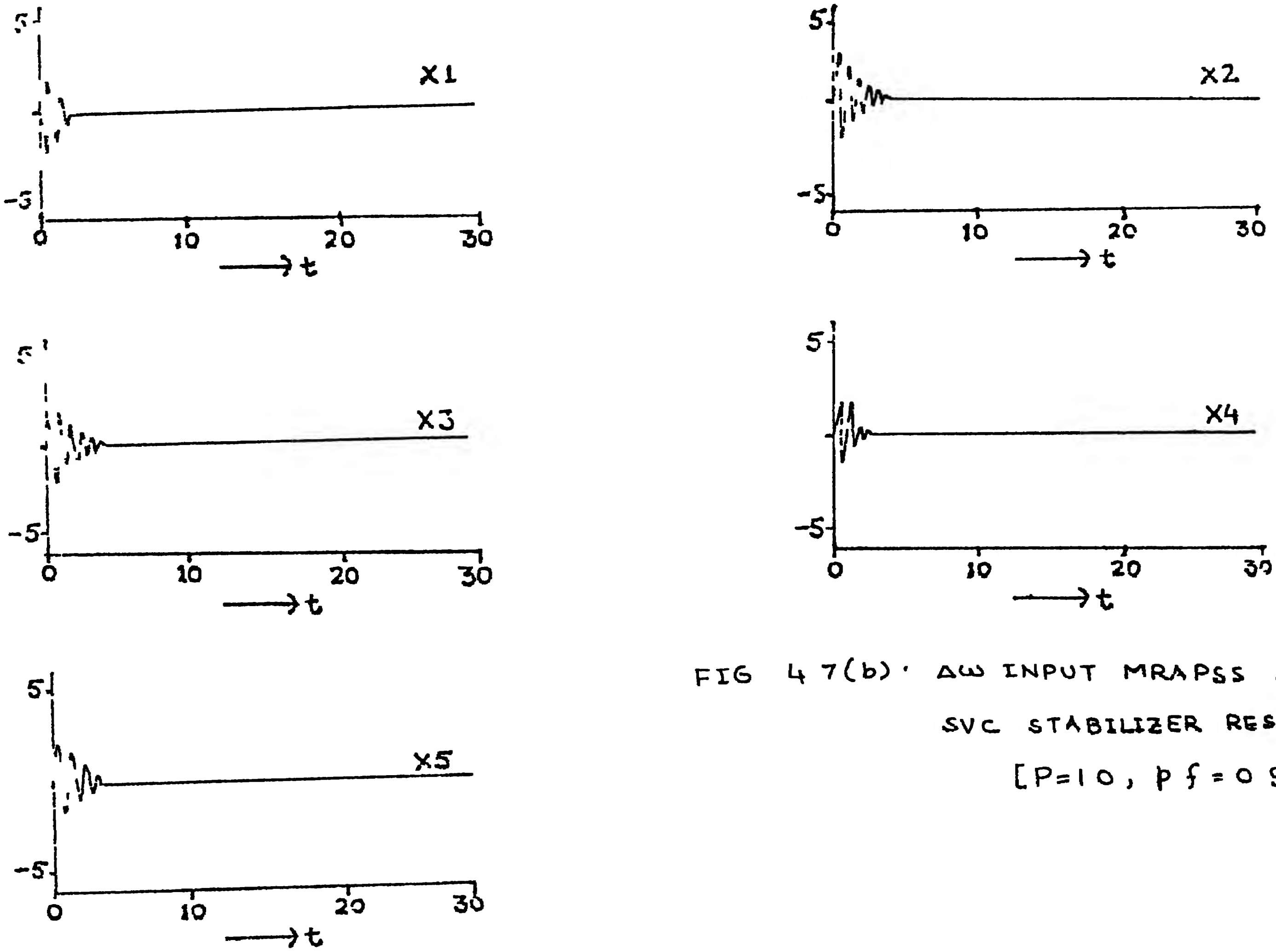
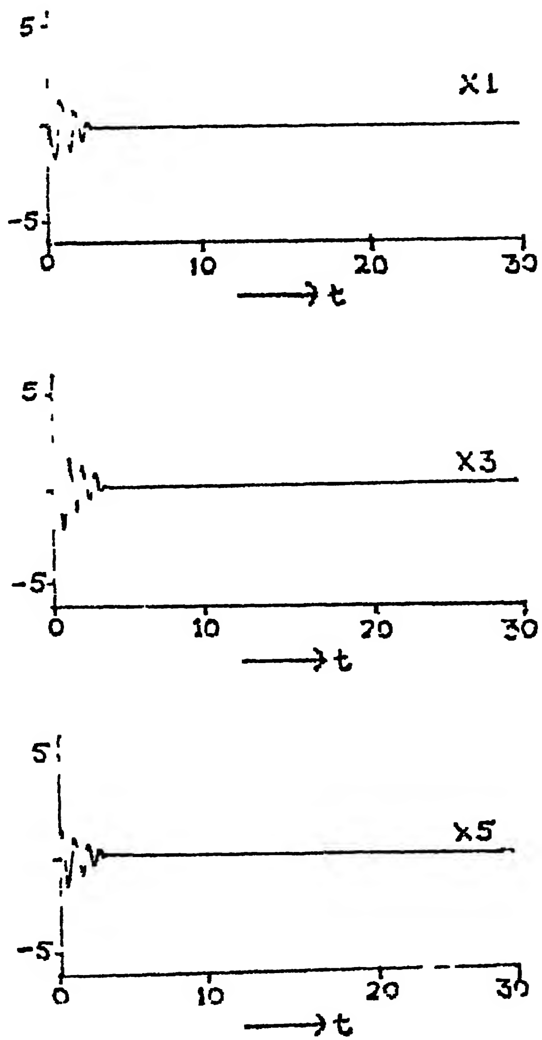


FIG 4 7(b)· $\Delta\omega$ INPUT MRAPSS AND ΔQ_m INPUT SVC STABILIZER RESPONSE

[P=1 0 , p f = 0 9 LAG]



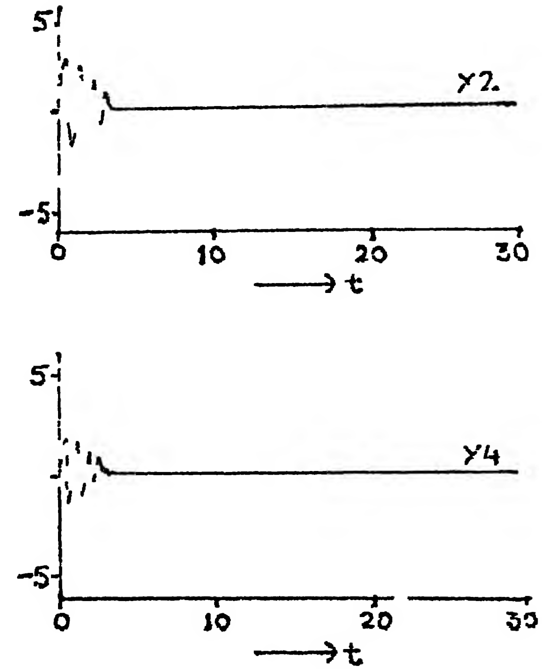


FIG 4 7(C). $\Delta\omega$ INPUT MRAPSS AND ΔQ_m INPUT SVC STABILIZER RESPONSE

[P = 0.8, pf = 0.8 LAG]

CHAPTER - 5

SIMULATION STUDY USING SPEED SIGNAL MRAPSS

In chapter 4, the MRAC technique based controllers were designed for both PSS and SVC. Simultaneous operation of the two controllers was studied It was found that the behaviour of controllers was quite good near the design point i e. for small variation around the design point

In power systems, generally large and sudden changes in operating conditions are rare, the changes occur slowly It can be said that large changes are a sequency of small changes occurring slowly. These changes are expected to be tracked efficiently by the control system designed The actual system parameters (along with feedback) can be expected to be close to model parameters at any time This justifies use of model parameters for estimating states through observers in the design methodology followed. It is necessary the study of controller behaviourfor ,conditions of slow but eventually large changes in operating conditions.

The simulation study for such changes was carried out to study the behaviour of MRAC technique based controller developed.For such study speed signal based MRAPSS was considered. It was assumed that large changes occured in power supplied These changes were broken into small changes The controller was tested for these changes Final conditions for one stage become initial conditions for the other stage. It is important to note that no linearization was made and the actual equations (not the linearized

ones) were used [31]. Software package SIMNON was used for simulation Results of simulation are presented in Figures 5 1 (a), 5.1 (b), 5 1 (c), 5.1 (d), 5.1 (e), 5.1 (f) at the end of this chapter

It is seen by simulation that the behaviour of controller is satisfactory for even very large changes provided they occur very slowly and hence dynamic stability of the system is ensured.

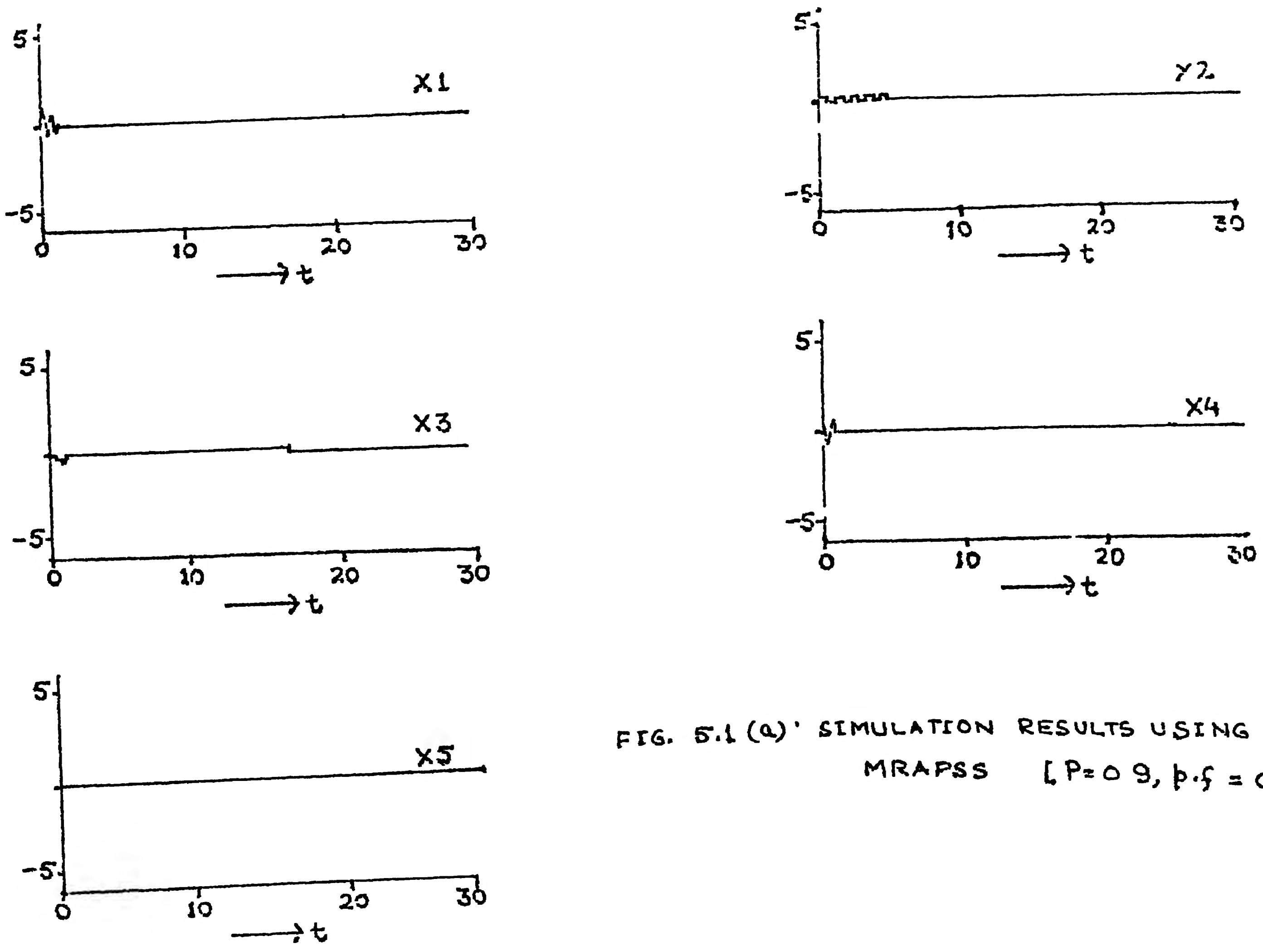


FIG. 5.1 (a) SIMULATION RESULTS USING $\Delta\omega$ INPUT MRAPSS [P = 0.9, p.f = 0.9 LAG]

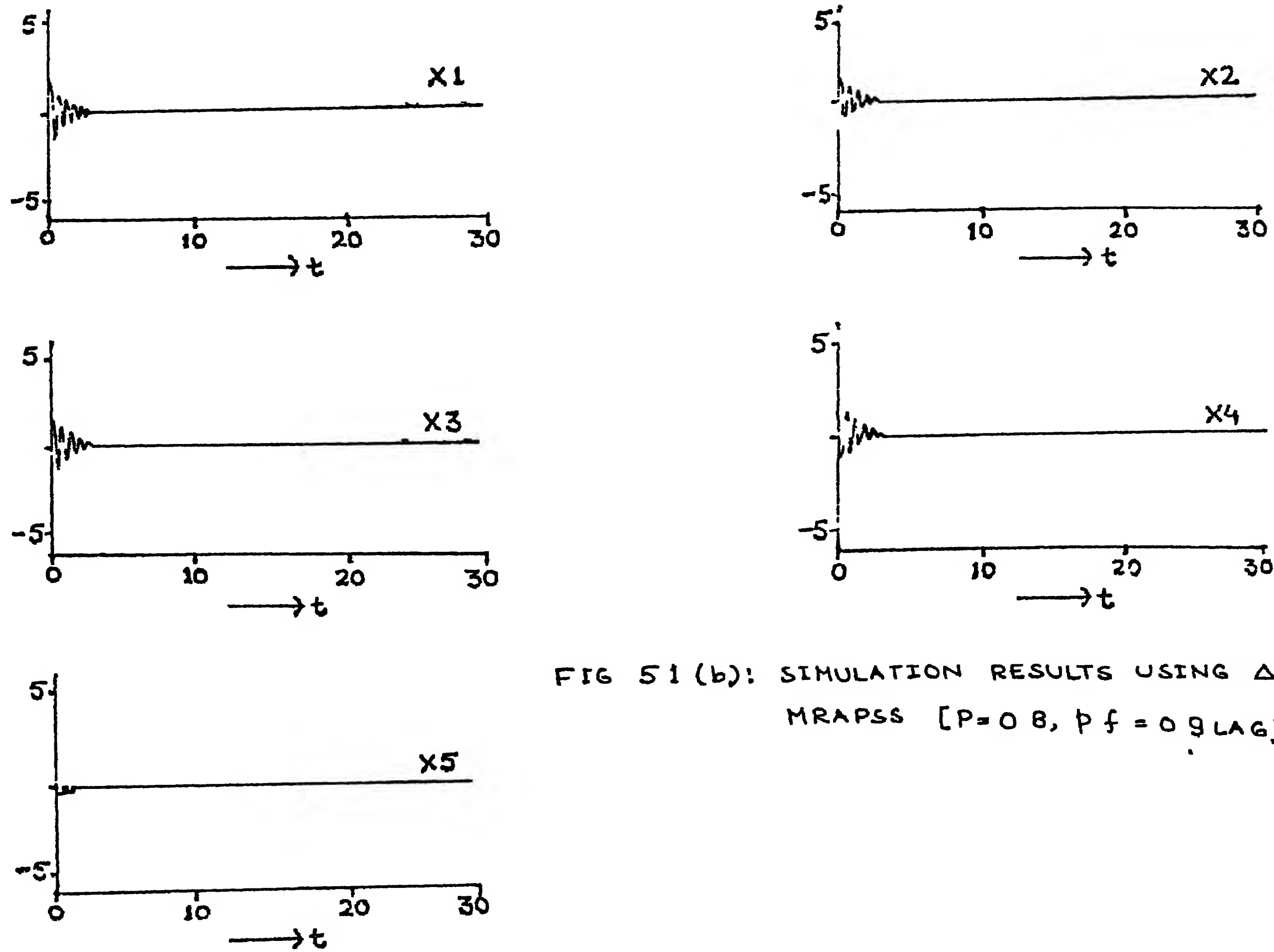


FIG 5 1 (b): SIMULATION RESULTS USING $\Delta\omega$ INPUT MRAPSS [P= 0 8, pf = 0 9 LAG]

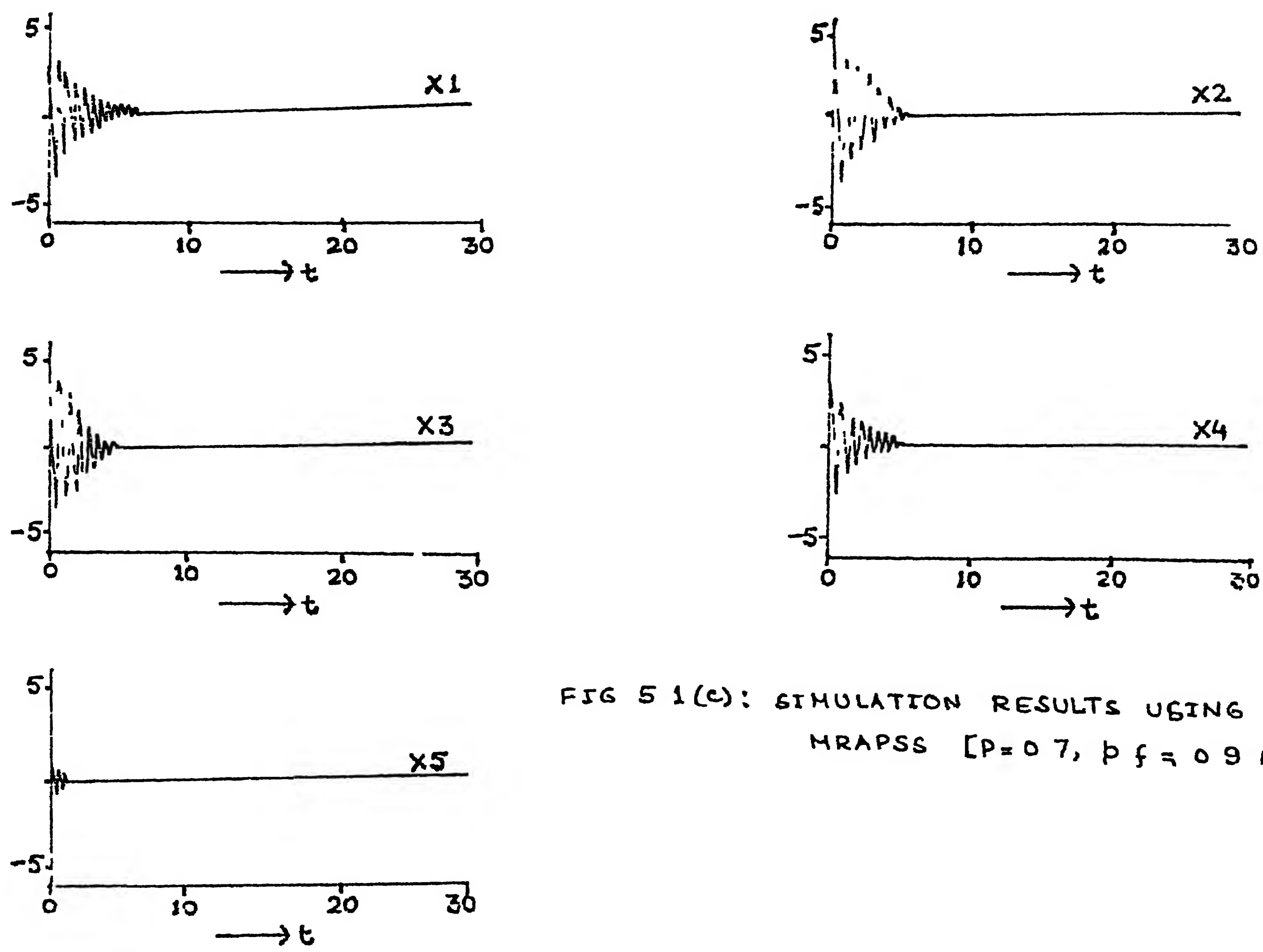


FIG 5 1(c): SIMULATION RESULTS USING $\Delta\omega$ INPUT MRAPSS [P= 0 7, p f = 0 9 LAG]

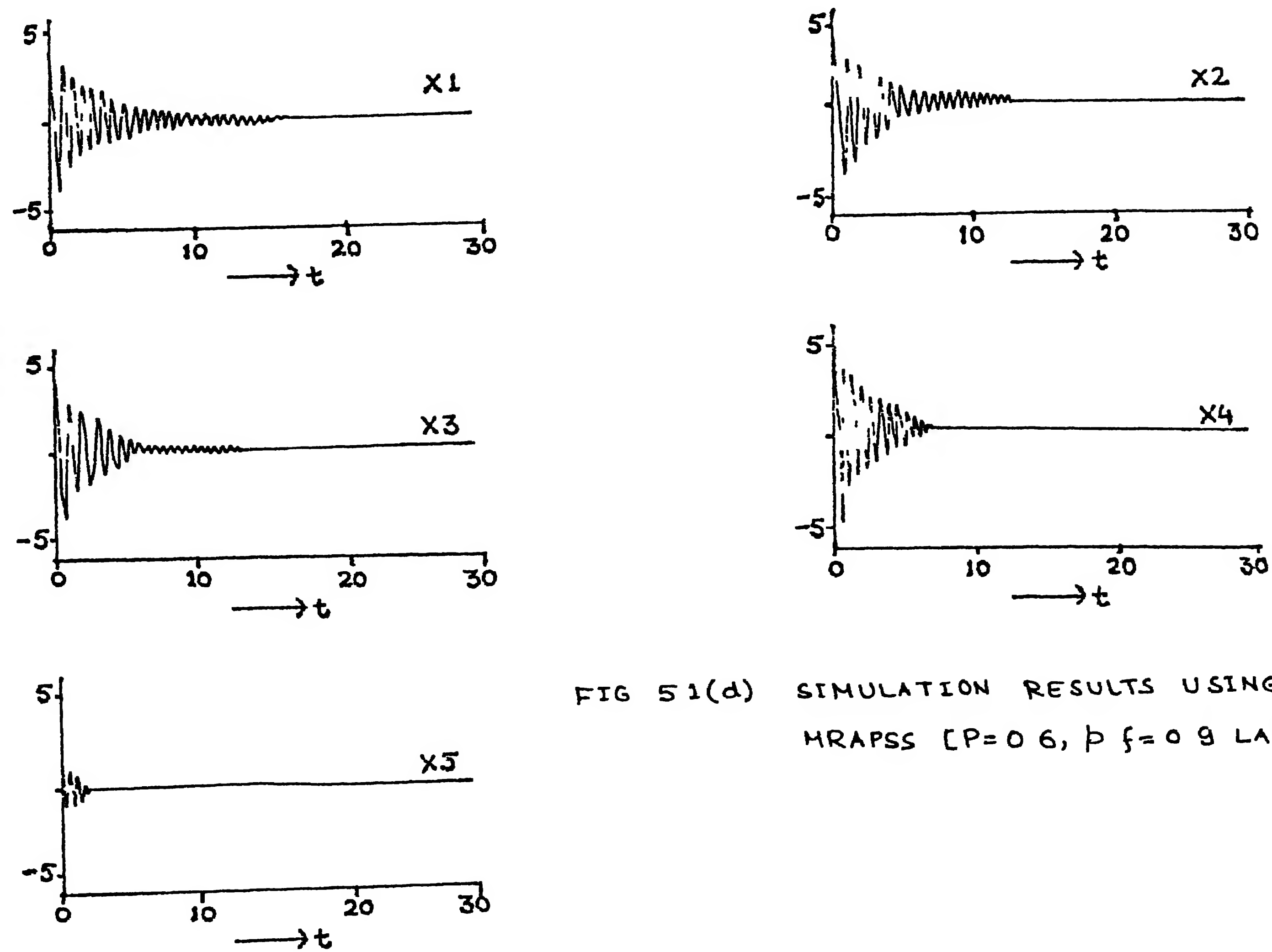


FIG 5 1(d) SIMULATION RESULTS USING $\Delta\omega$ INPUT
MRAPSS [P=0 6, P f=0 9 LAG]

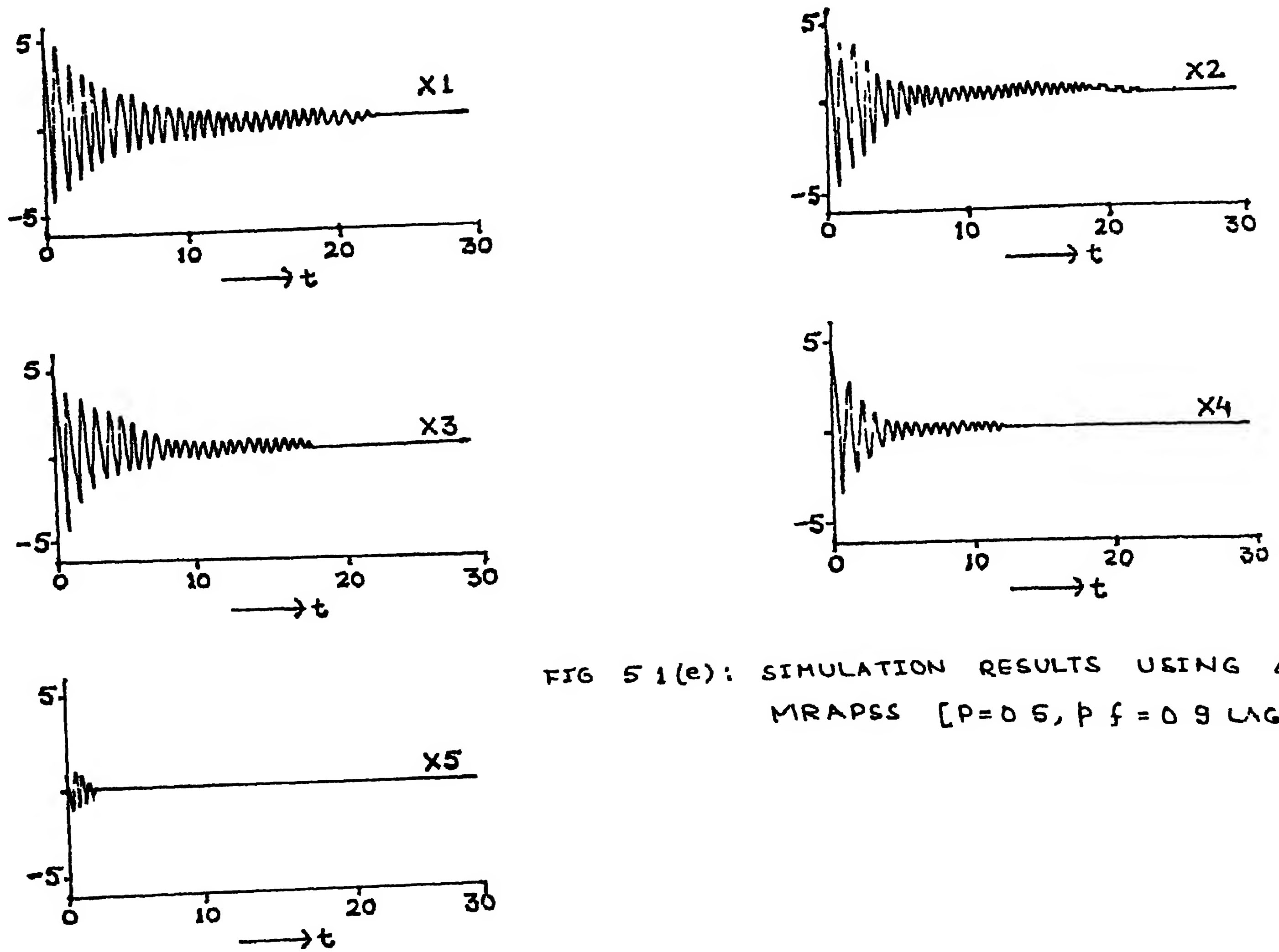


FIG 5 1(e): SIMULATION RESULTS USING $\Delta\omega$ INPUT MRAPSS [P = 0 5, p f = 0 9 LAG]

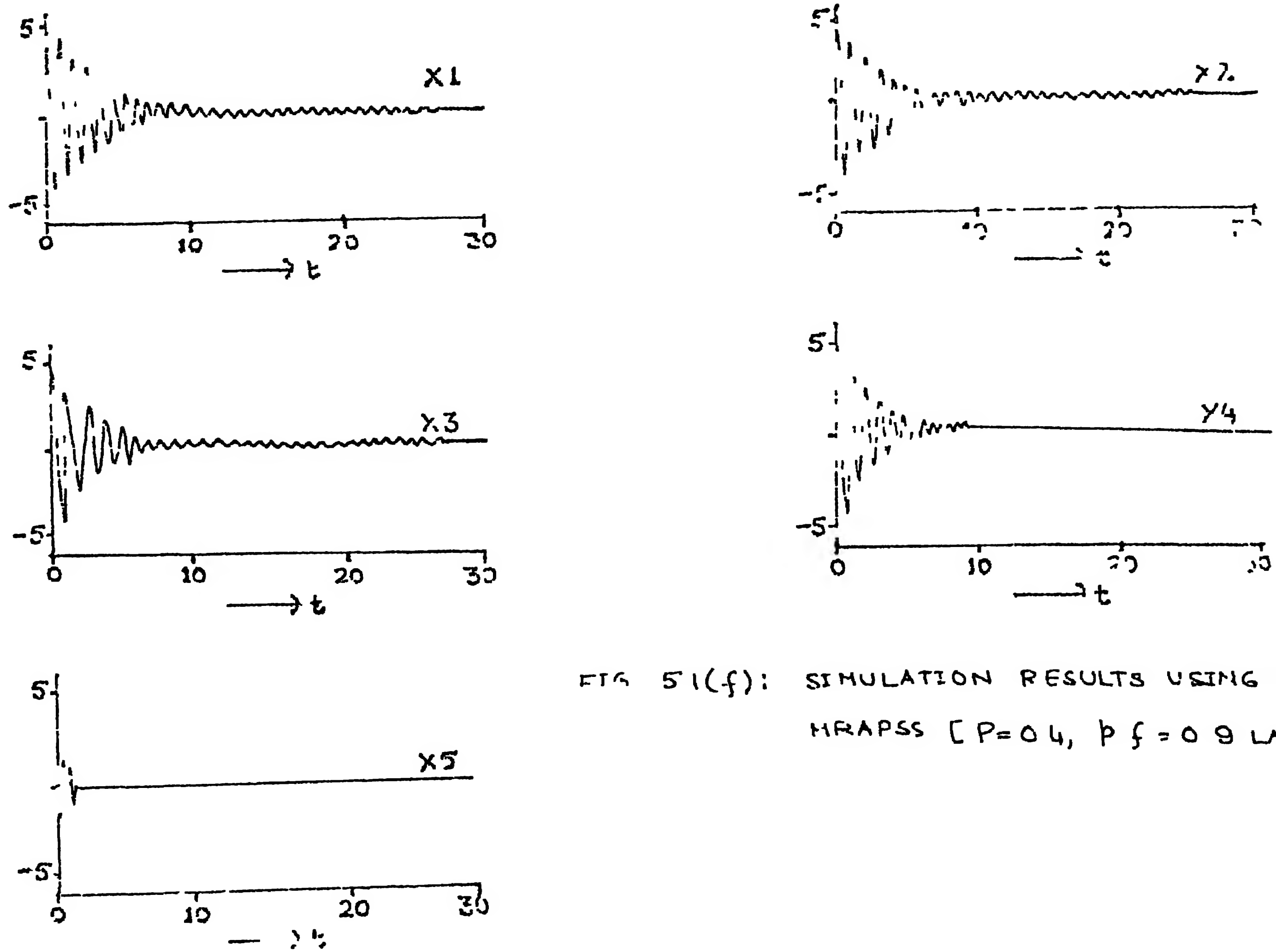


FIG 5.1(f): SIMULATION RESULTS USING Δω INPUT
HRAPSS [P=0.4, Pf=0.9 LAG]

CHAPTER - 6

RESULTS AND SCOPE FOR FUTURE WORK

6 1 RESULTS

1 MRAPSS & MRASVC controllers were designed and tested for various operating points For PSS design $\Delta\omega$ & ΔP_e signals were used while for SVC stabilizer design ΔP_m & ΔQ_m signals were used.

2. The adaptive character was clearly visible in operating range near the design point The best performance was obtained near designed point

3. For higher loading (loading slightly higher, by about 10%) the performance of controllers was satisfactory underlining the efficacy of the procedure.

4 In simultaneous operation of stabilizers, it was observed that ΔP_e input PSS & ΔP_m or ΔQ_m input SVC stabilizers reacted adversely The other combinations $\Delta\omega$ input PSS & ΔP_m or ΔQ_m input SVC stabilizers improved the system performance in very limited range

5. With the help of $\Delta\omega$ input MRAPSS it was shown that MRAC technique based controllers can operate satisfactorily for a large change provided the change takes place very slowly This result is of great significance keeping operation of modern plants in mind

6.2 SCOPE OF FUTURE WORK

The MRAC technique based controllers have been studied

for dynamic stability It can be an interesting work to analyse their efficacy for transient stability.

The analysis for controllers has been carried out for a simplified single machine infinite bus system It will be interesting to study their interactions for multi machine systems.

Some other possible works include options of variable reference model and more detailed study of coordination of controllers

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APPENDIX - A

MODEL OF POWER SYSTEM

A 1 DEVELOPMENT OF THE MODEL

The power system consists of a synchronous generator connected to an infinite bus through a transmission line. Static VAR compensator (SVC) is installed at the midpoint of the transmission line.

The following assumptions are made for developing a state space model of the system.

1. The synchronous machine has no damper windings.
2. Governer and turbine dynamics can be ignored.
3. The machine stator and external network are in quasi steady state
4. Magnetic saturation in generator is neglected

A.1 1 Generator Model

A third order generator model is considered. The equation and notations are standard. The equations are given below

$$pE_q' = -\frac{E_q'}{T'_{do}} + \frac{E_{FD}}{T'_{do}} + (X_d - X_d')I_d \qquad (A.1)$$

$$p\omega = \frac{1}{M}(T_m - Te) - \frac{K_d}{M}(\omega - \omega_o) \qquad (A.2)$$

$$p\delta = \omega - \omega_o \qquad (A.3)$$

$$M = \frac{2H}{\omega_o}$$

$$Te = (V_d\ I_d + V_q\ I_q)$$

$$V_d = -X_q I_q$$

$$V_q = X_{d'}\ I_d + E_{q'} \qquad (A.4)$$

All quantities are in p u. except δ and ω, which are in radian and rad/sec. respectively

A.1 2 Excitation System Model

A single time constant excitation system, IEEE type 1S is considered Block diagram representation of this system is shown in fig 2.2

The dynamical equation representing the excitation system is

$$pE_{FD} = -\frac{E_{FD}}{T_A} + \frac{K_A}{T_A}(V_{ref} - V_t + V_{ss}) \qquad (A.5)$$

Where V_t can be represented in terms of Park's voltages as

$$V_t = (V_d^2 + V_q^2)^{1/2}$$

where $V_d = -X_q\ I_q$

$V_q = X'_d\ I_d + E'_q$

A 1 3 SVC Model

A single time constant SVC voltage controller is

considered The block diagram representation of SVC controller is given in Fig 2.5.

The dynamical equation representating SVC voltage controller is

$$pB = -\frac{B}{T_B} + \frac{K_B}{T_B}(V_{mref} - V_m + V_{se}) \tag{A.6}$$

A 1 4 <u>Linearized Model</u>

The linearized state space model is derived by linearizing equations (A.1), (A.2), (A.3), (A.5) and (A 6). The non state variables I_d, T_e, ΔV_t and ΔV_m are represented in terms of state variables as follows.

A.1 4 1 <u>Expression for ΔI_d and ΔI_q</u>

To obtain expressions for ΔI_d and ΔI_q in terms of state variables the system in Fig. 2.1 is reduced to form shown in Fig. A 1 by star-delta transformation. The impedance then reflecting between the infinite bus and the ground can be neglected

For the system in Fig. A 1, we can write the following equations as in [25, sec. 5 4],

$$V_d(1 + \lambda_1) + V_q \lambda_2 = -V_\infty \sin(\delta - \alpha) + R_e I_d + X_e I_q \tag{A.7}$$

$$-V_d\lambda_2 + V_q(1 + \lambda_1) = V_\infty \cos(\delta - \alpha) - X_e I_d + R_e I_q \tag{A.8}$$

where α and δ areas defined in [25, sec 5 4],

$$R_{10} - R \quad , R_e = (2R - 2RBx)$$

$$X_{10} = (X - \frac{2}{B}) \quad , X_e = (R^2B - X^2B + 2X)$$

$$Z_{10}^2 = R^2 + (X - \frac{2}{B})^2$$

$$\lambda_1 = \frac{(R_{10}\ R_e + X_{10}\ X_e)}{Z_{10}^2} \qquad \lambda_2 = \frac{(R_{10}\ X_e - X_{10}\ R_e)}{Z_{10}^2}$$

$$= -\ BX \qquad\qquad = RB \tag{A.9}$$

Linearizing equation (A.7) and (A 8) we obtain expression for ΔI_d and ΔI_q in terms of state variables as

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{bmatrix} \begin{bmatrix} \Delta Eq' \\ \Delta\delta \\ \Delta B \end{bmatrix} \tag{A.10}$$

Where

$$b_{11} = -\left[\frac{b_5\ B_o - b_2(1 - B_oX)}{b_1b_5 - b_2b_4}\right] \tag{A.11}$$

$$b_{12} = -\left[\frac{b_5V_\infty \operatorname{Cos}(\delta_0 - \alpha) - b_2V_\infty \operatorname{Sin}(\delta_o - \alpha)}{b_1b_5 - b_2b_4}\right] \tag{A.12}$$

$$b_{13} = \left[\frac{b_3\ b_5 - b_2b_6}{b_1b_5 - b_2b_4}\right] \tag{A.13}$$

$$b_{21} = - \left[\frac{b_4 B_o - b_1(1 - B_o X)}{b_2 b_4 - b_1 b_5} \right] \quad (A.14)$$

$$b_{12} = - \left[\frac{b_4 V_\infty \mathrm{Cos}(\delta_0 - \alpha) - b_1 V_\infty \mathrm{Sin}(\delta_o - \alpha)}{b_2 b_4 - b_1 b_5} \right] \quad (A\ 15)$$

$$b_{23} = \left[\frac{b_3 b_4 - b_1 b_6}{b_2 b_4 - b_1 b_5} \right] \quad (A.16)$$

In the above equations

$$b_1 = [B_o X_d' R - 2R + 2B_o RX]$$

$$b_2 = [- X_q + B_o X_q X - R^2 B_o + X^2 B_o - 2X]$$

$$b_3 = - [I_{qo} X_q X + I_{do} X_d' R + E_q' R_o + 2I_{do} RX$$

$$- I_{qo} R^2 + I_{qo} X^2]$$

$$b_4 = [X_d' - X_d' XB_o + R B_o^2 - X B_o^2 + 2X]$$

$$b_5 = [X_q RB_o - 2R + 2RXB_o]$$

$$b_6 = - [X_q RI_{qo} - X_d' X I_{do} - XE'_{qo} + R^2 I_{do}$$

$$- X^2 I_{do} + 2RXI_{qo}] \quad (A.17)$$

A.1 4 2 Expression for ΔT_e

$$T_e = (V_d I_d + V_q I_q)\ p\ u.$$

where,

$$V_d = -X_q I_q$$

$$V_q = + X'_d \quad I_d + E'_q$$

Therefore,

$$T_e = [E'_q \quad I_q - (X_q - X'_d) I_d I_q] \tag{A.18}$$

Linearizing equation (A.18) and then substituting for ΔI_d and ΔI_q from equation (A 10) we get

$$\Delta T_e = M[b_{40} \; \Delta E'_q \; + b_{42} \; \Delta\delta + b_{43} \; \Delta B] \tag{A.19}$$

where,

$$b_{40} = [b_{21}(E'_{qo} - X_q I_{do} + X'_d \; I_{do}) + b_{11}(I_{qo} X'_d \; - I_{qo} X_q) + I_{qo}]$$

$$b_{41} = [b_{22}(E'_{qo} - X_q I_{do} + X'_d \; I_{do}) + b_{12}(I_{qo} X'_d \; - I_{qo} X_q)]$$

$$b_{42} = [b_{23}(E'_{qo} - X_q I_{do} + X'_d \; I_{do}) + b_{13}(I_{qo} X'_d \; - I_{qo} X_q)]$$

(A.20)

A 1 4.3 Expression for ΔV_t

For generator terminal voltage V_t we can write

$$V_t^2 = V_d^2 + V_q^2 \tag{A.21}$$

Linearizing above equation and substituting for ΔI_d and ΔI_q from equation (A.10) we can write

$$\Delta V_t = K_6 \; \Delta E'_q \; + K_5 \; \Delta\delta + K_9 \; \Delta B \tag{A.22}$$

where,

$$K_6 = -\frac{V_{do}}{V_{to}} X_q b_{21} + \frac{V_{qo}}{V_{to}} X'_d \, b_{11} + \frac{V_{qo}}{V_{to}}$$

$$K_5 = -\frac{V_{do}}{V_{to}} X_q b_{22} + \frac{V_{qo}}{V_{to}} X'_d \, b_{12}$$

$$K_9 = -\frac{V_{do}}{V_{to}} X_q b_{23} + \frac{V_{qo}}{V_{to}} X'_d \, b_{13}$$

A.1 4 4 Expression for ΔV_m

For SVC bus voltage V_m we can write

$$V_m^2 = V_{mq}^2 + V_{md}^2 \tag{A.24}$$

where,

$$V_{md} = V_d - I_d R - I_q X$$

$$V_{mq} = V_q - I_q R - I_q X$$

Linearizing equation (A 24) and substituting for ΔI_d and ΔI_q from (A 10) we get,

$$\Delta V_m = b_{56} \, \Delta E'_q + b_{57} \, \Delta\delta + b_{58} \, \Delta B \tag{A.25}$$

where,

$$b_{56} = \frac{V_{mdo}}{V_{mo}} b_{50} + \frac{V_{mqo}}{V_{mo}} b_{53}$$

$$b_{57} = \frac{V_{mdo}}{V_{mo}} b_{51} + \frac{V_{mqo}}{V_{mo}} b_{54}$$

$$b_{58} = \frac{V_{mdo}}{V_{mo}} b_{52} + \frac{V_{mqo}}{V_{mo}} b_{55} \qquad (A.26)$$

The final state equations are obtained after substituting for ΔI_d, ΔT_e, ΔV_t and ΔV_m in terms of state variables in equations (A.1), (A.2), (A.3), (A.5) and (A.6). The resulting fifth order system state equation can be written as,

$$\underline{X} = A\underline{X} + \underline{b}_1 u_1 + \underline{b}_2 u_2 \qquad (A.27)$$

where,

$$\underline{X} = [\Delta E_q' \quad \Delta\omega \quad \Delta\delta \quad \Delta E_{FD} \quad \Delta B]^t \qquad (A\ 28)$$

and $u_1 = \Delta V_{ss}$, stabilizing signal from PSS

$u_2 = \Delta V_{se}$, stabilizing signal from SVC stabilizer (A.29)

A_1 , b_1 and b_2 matrices are given as

$$A = \begin{bmatrix} A_{11} & 0 & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & 0 & A_{25} \\ 0 & A_{32} & 0 & 0 & 0 \\ A_{41} & 0 & A_{43} & A_{44} & A_{45} \\ A_{51} & 0 & A_{53} & 0 & A_{55} \end{bmatrix} \qquad (A.30)$$

$$\underline{b}_1 = [\,0 \quad 0 \quad 0 \quad b_4 \quad 0]^t \qquad (A.31)$$

$$\underline{b}_2 = [0 \quad 0 \quad 0 \quad 0 \quad b_5]^t \qquad (A.32)$$

$$A_{11} = \frac{[(X_d - X_d')b_{11} - 1]}{T_d'}$$

$$A_{13} = \frac{(X_d - X_d')b_{12}}{T_d'}$$

$$A_{14} = \frac{1}{T_{do}'}$$

$$A_{15} = \frac{(X_d - X_d')b_{13}}{T_d'}$$

$$A_{21} = - \frac{b_{40}}{M}$$

$$A_{22} = - \frac{K_D}{M}$$

$$A_{23} = - \frac{b_{41}}{M}$$

$$A_{25} = - \frac{b_{42}}{M}$$

$$A_{32} = 1$$

$$A_{41} = - \frac{K_6 K_A}{T_A}$$

$$A_{43} = - \frac{K_5 K_A}{T_A}$$

$$A_{44} = -\frac{1}{T_A}$$

$$A_{45} = -\frac{K_9 K_A}{T_A}$$

$$A_{51} = -\frac{K_B b_{56}}{T_B}$$

$$A_{53} = -\frac{K_B b_{57}}{T_B}$$

$$A_{55} = -\frac{(1 + K_B b_{58})}{T_B}$$

$$b_4 = \frac{K_A}{T_A}$$

$$b_5 = \frac{K_B}{T_B} \tag{A.33}$$

A.1 5 Output Equations

The output equation of the system can be written as,

$$y_1 = c_1 \underline{x}$$

where y_1 represents input to PSS, and

$$y_2 = c_2 \underline{x}$$

where y_2 represents input to SVC stabilizer

The elements of matrices c_1 and c_2 depend upon the particular variables chosen as y_1 and y_2

A 1.5 1 Output Equations Corresponding to PSS Signals

For PSS we have considered rotor speed and generator active power as control signal

Speed Signal .

Change in rotor speed ($\Delta\omega$) is utilized as control signal. Since speed is one of the state variables in our system model, the output equation is directly obtained as,

$$y_1 = [\Delta\omega] = [0 \quad 1 \quad 0 \quad 0 \quad 0]\,\underline{x} \qquad \text{(A.34)}$$

Thus,

$$c_1 = [0 \quad 1 \quad 0 \quad 0 \quad 0] \qquad \text{(A.35)}$$

Power Signal :

Generator power output is taken as control signal. When expressed in p.u, $\Delta P_e = \Delta T_e$.

Hence, we can write the output equation corresponding to power signal as,

$$y_1 = [\Delta P_e] = [b_{40} \quad 0 \quad b_{41} \quad 0 \quad b_{42}]\,\underline{x} \qquad \text{(A.36)}$$

Thus,

$$c_1 = [b_{40}\ ,\ 0\quad b_{41}\quad 0\quad b_{42}]\ \underline{x} \tag{A.37}$$

where b_{40} , b_{41} and b_{42} are as given in expression for ΔT_e.

A 1 5 2 <u>Output Equations Corresponding to SVC Stabilizer Signals</u>

For SVC stabilizer we have considered mid line power and mid line reactive power signals.

Mid line Active Power Signal.

Mid line active power is given as,

$$P_m = [V_{md} I_d + V_{mq} I_q] \tag{A 38}$$

Linearizing the above expression and manipulating we get,

$$\Delta P_m = b_{60}\ \Delta E_q' + b_{61}\ \Delta\delta + b_{62}\ \Delta B \tag{A.39}$$

Thus,

$$C_2 = [b_{60}\quad 0\quad b_{61}\quad 0\quad b_{62}] \tag{A.40}$$

where,

$$b_{60} = b_{11}\ V_{mdo} + b_{50}\ I_{do} + b_{21}\ V_{mqo} + b_{53}\ I_{qo}$$

$$b_{61} = b_{12}\ V_{mdo} + b_{51}\ I_{do} + b_{22}\ V_{mqo} + b_{54}\ I_{qo}$$

$$b_{62} = b_{13}\ V_{mdo} + b_{52}\ I_{do} + b_{23}\ V_{mqo} + b_{55}\ I_{qo} \tag{A.41}$$

In the above equation :-

$$b_{50} = [(-X_q - X)b_{21} - Rb_{11}]$$

$$b_{51} = [(-X_q - X)b_{22} - Rb_{12}]$$

$$b_{52} = [(-X_q - X)b_{23} - Rb_{13}]$$

$$b_{53} = [\ -Rb_{21} + (\ X + X_d')b_{11} + 1]$$

$$b_{54} = [\ -Rb_{22} + (\ X + X_d')b_{12}]$$

$$b_{55} = [\ -Rb_{23} + (\ X + X_d')b_{13}] \qquad (A.42)$$

Mid line reactive power signal:

Mid line reactive power is given by

$$Q_m = [V_{md}I_q - V_{mq}I_d]$$

linearizing the above expression and manipulating we get,

$$\Delta Q_m = b_{80}\ \Delta E_q' + b_{81}\ \Delta\delta + b_{82}\ \Delta B \qquad (A\ 43)$$

$$\text{Thus } C_2 = [b_{80} \quad 0 \quad b_{81} \quad 0 \quad b_{82}] \qquad (A.44)$$

where,

$$b_{80} = b_{21}V_{mdo} + B_{70}I_{do} - b_{11}V_{mqo} + b_{73}I_{qo}$$

$$b_{81} = b_{22}V_{mdo} + B_{71}I_{do} - b_{12}V_{mqo} + b_{74}I_{qo}$$

$$b_{82} = b_{23}V_{mdo} + B_{72}I_{do} - b_{13}V_{mqo} + b_{75}I_{qo} \qquad (A.45)$$

In the above equation -

$$b_{70} = - [-Rb_{21} + (X + X_d')b_{11} + 1]$$

$$b_{71} = - [-Rb_{22} + (X + X_d')b_{12}]$$

$$b_{72} = - [-Rb_{23} + (X + X_d')b_{13}]$$

$$b_{73} = [(-X_q - X)b_{21} - Rb_{11}]$$

$$b_{74} = [(-X_q - X)b_{22} - Rb_{12}]$$

$$b_{75} = [(-X_q - X)b_{23} - Rb_{13}]$$

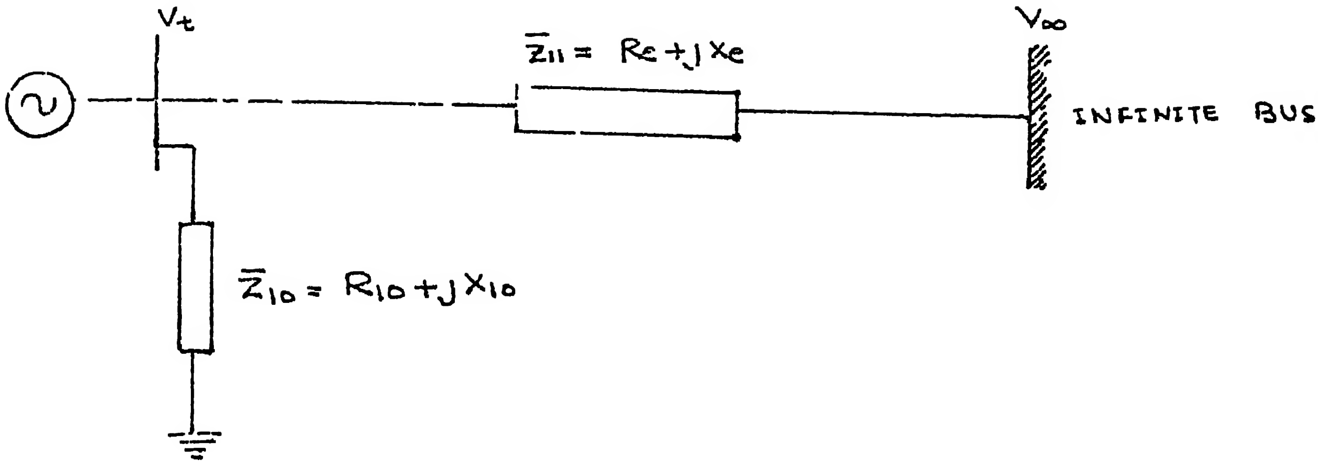

FIG A.1 : EQUIVALENT CIRCUIT OF THE SYSTEM

APPENDIX - B

POWER SYSTEM DATA

Most of the data are as in [17]. All quantities are expressed in p.u on a 500 kV, 5000 MVA base.

1. **GENERATOR**

$X_d = 1.7$ $X_q = 1\ 64$ $X'_d = .345$

$T'_{do} = 6\ 4$ $H = 1\ 6$ $wo = 314$

2. **EXCITATION SYSTEM**

$K_A = 50$ $T_A = \ 01$ sec.

3 **SVC VOLTAGE CONTROLLER**

$K_B = 20$ $T_B = \ 02$ sec.

4. **NETWORK PARAMETERS**

(i) Step up transformer $X_t = .15$ (Ignored in analysis)

(ii) Transmission line (500 kV, 100 km, line constants per circuit).

$R_{line} = 0.0135$

$X_{line} = 0.452$

$B_{line} = 0.02294$

5 **INFINITE BUS VOLTAGE** = $1\ 0\ \underline{|0}$ p u

6 $K_D = 0$

APPENDIX - C

SELECTION OF REFERENCE MODEL

Selection of reference model is based on the concept of pole placement. Ref. [30] shows that a controllable system is always pole assignable by appropriate state feedback. The concept will be restricted to single input linear systems. We have

$$\underline{X} = A\,\underline{X} + \underline{b}\,u \tag{C.1}$$

and

$$\underline{y} = C\,\underline{X} \tag{C.2}$$

The idea is to find a law of type

$$u = K\,\underline{X} + r \tag{C.3}$$

Such that

$\underline{X} = (A + \underline{b}\,K)\,\underline{X} + \underline{b}\,r$ has desired pole locations.

$(A + \underline{b}\,K)$ will be termed as reference model

This objective is achieved in following steps :-

1 The system is cast into controllable companion form. Since $\{A,b\}$ is controllable there exists a transformation matrix $P(\bar{X} = P\underline{X})$ which converts (c 1) into the following form.

$$\bar{X} = \bar{A}\,\bar{X} + \bar{b}\,u$$

Where

$$\bar{A} = PAP^{-1} = \begin{bmatrix} 0 & 1 & 0 & . & . & 0 & 0 \\ 0 & 0 & 1. & & . & 0 & 0 \\ & . & . & . & .. & .. & . & . \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\alpha_n & -\alpha_{n-1} & & . & & . & . -\alpha_1 \end{bmatrix}, \quad \bar{b} = P\underline{b} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

(C.4)

Here coefficients α_i $(i = 1,2,. \; .n)$ are coefficients of characteristic polynomial of (c.1).

2. Because of equivalence transformation, the feedback control law becomes

$$u = K\,\underline{X} + r$$

$$= K\,P^{-1}\,\bar{X} + r$$

$$\triangleq \bar{K}\,\bar{X} + r \qquad \text{(C 5)}$$

where

$$\bar{K} = K\,P^{-1} = [\bar{K}_1 \;\; \bar{K}_2 \;\; \ldots K_n) \qquad \text{(C.6)}$$

With this law system (c 4) becomes

$$\bar{X} = \begin{bmatrix} 0 & 1 & 0 \ldots . & 0 & 0 \\ 0 & 0 & 1 \ldots . & 0 & 0 \\ . & \ldots\ldots & .. \; .. \; .. & . & .. \\ 0 & 0 & 0 & 0 & 1 \\ -\alpha_n + \bar{K}_1 & & & -\alpha_1 & + \bar{K}_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

(C.7)

Since coefficients $\bar{K}_1$ are arbitrarily chosen real numbers, the coefficients of charac teristic polynomial of $(\bar{A} + \bar{b}\,\bar{K})$ can be given any desired values.

3. Assuming the desired characteristic polynomial of $(A + b\,K)$ and hence $(\bar{A} + \bar{b}\,\bar{K})$ is

$$s^n + \bar{\alpha}_1 s^{n-1} + . + \bar{\alpha}_n \qquad (C.8)$$

From (c.7), it is obvious that this requirement is met if $\bar{K}$ is chosen as

$$\bar{K} = [\alpha_n - \bar{\alpha}_n \quad \alpha_{n-1} - \bar{\alpha}_{n-1} \ldots \,..\alpha_1 - \bar{\alpha}_1] \qquad (C.9)$$

To obtain K the system is converted to original coordinates by transformation

$$K = \bar{K}\,P$$

By proper selection of K, the reference model with desired pole location is obtained.

APPENDIX - D

CONSTRUCTION OF FOURTH ORDER OBSERVER

In a n^{th} order system, if q state variables can be directly obtained from q outputs (available for measurement), then remaining (n - q) state variables can be obtained using an observer of order (n - q).

For PSS and SVC controllers such a case exists only for PSS with $\Delta\omega$ as input signal Since the parameter matrices A and B of the plant are not known, the observer is designed using parameter matrices A_m and B_m of the reference model.

So,

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} = \begin{bmatrix} A_{m11} & 0 & A_{m13} & A_{m14} & A_{m15} \\ A_{m21} & A_{m22} & A_{m23} & 0 & A_{m25} \\ 0 & A_{m32} & 0 & 0 & 0 \\ A_{m41} & A_{m42} & A_{m43} & A_{m44} & A_{m45} \\ A_{m51} & 0 & A_{m53} & 0 & A_{m55} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b_4 \\ 0 \end{bmatrix} u \tag{D.1}$$

Since state X_2 ($\Delta\omega$) is directly available the state equations expressed in standard form [30] are,

We can derive the following equations by substituting equation (D 6) in equations (D 3) and (D 4)

$$z_1 = B_{11} + B_{12}z_2 + B_{13}z_3 + B_{14}z_4 + (C_1 - D_1)X_2$$

$$z_2 = B_{21} + B_{22}z_2 + B_{23}z_3 + B_{24}z_4 + (C_2 - D_2)X_2$$

$$z_3 = B_{31} + B_{32}z_2 + B_{33}z_3 + B_{34}z_4 + (C_3 - D_3)X_2 + b_4u$$

$$z_4 = B_{41} + B_{42}z_2 + B_{43}z_3 + B_{44}z_4 + (C_4 - D_4)X_2 \qquad (D.7)$$

$$\hat{X}_1 = z_1 - m_1X_2$$

$$\hat{X}_3 = z_2 - m_2X_2$$

$$\hat{X}_4 = z_3 - m_3X_2$$

$$\hat{X}_5 = z_4 - m_4X_2 \qquad (D.8)$$

where

$$B_{11} = A_{m11} + m_1A_{m21}$$

$$B_{12} = A_{m13} + m_1A_{m23}$$

$$B_{13} = A_{m14}$$

$$B_{14} = A_{m15} + m_1A_{m25}$$

$$B_{21} = m_2A_{m21}$$

$$B_{22} = m_2A_{m23}$$

$$B_{23} = 0$$

$$B_{24} = m_2A_{m25}$$

$$B_{31} = A_{m41} + m_3A_{m21}$$

$$B_{32} = A_{m43} + m_3A_{m23}$$

$$B_{33} = A_{m44}$$

$$B_{34} = A_{m45} + m_3A_{m25}$$

$$B_{41} = A_{m51} + m_4 A_{m21}$$

$$B_{42} = A_{m53} + m_4 A_{m23}$$

$$B_{43} = 0$$

$$B_{44} = A_{m55} + m_4 A_{m25}$$

$$C_1 = m_1 A_{m22}$$

$$C_2 = m_2 A_{m22} + A_{m32}$$

$$C_3 = m_3 A_{m22} + A_{m42}$$

$$C_4 = m_4 A_{m22}$$

$$D_1 = B_{11} m_1 + B_{12} m_2 + B_{13} m_3 + B_{14} m_4$$

$$D_2 = B_{21} m_1 + B_{22} m_2 + B_{23} m_3 + B_{24} m_4$$

$$D_3 = B_{31} m_1 + B_{32} m_2 + B_{33} m_3 + B_{34} m_4$$

$$D_4 = B_{41} m_1 + B_{42} m_2 + B_{43} m_3 + B_{44} m_4 \qquad \text{(D.9)}$$

Equations (D 7), (D.8) and (D 9) give the fourth order observer equations.

APPENDIX - E

CONSTRUCTION OF FIFTH ORDER OBSERVER

If none of the state variables are available, fifth order observers are required. In our analysis such cases are:

1. PSS design with power signal.
2. SVC stabilizer design with Midline active power signal
3. SVC stabilizer design with Midline reactive power signal.

Since parameter matrices A and B and also the output matrix are not known, we take parameter matrices A_m and B_m of reference model and output matrix C_m at the design point of controllers.

So we have system representation as,

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} = \begin{bmatrix} A_{m11} & 0 & A_{m13} & A_{m14} & A_{m15} \\ A_{m21} & A_{m22} & A_{m23} & 0 & A_{m25} \\ 0 & A_{m32} & 0 & 0 & 0 \\ A_{m41} & A_{m42} & A_{m43} & A_{m44} & A_{m45} \\ A_{m51} & 0 & A_{m53} & 0 & A_{m55} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b_4 \\ 0 \end{bmatrix} u \tag{E.1}$$

(for PSS design)

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} = \begin{bmatrix} A_{m11} & 0 & A_{m13} & A_{m14} & A_{m15} \\ A_{m21} & A_{m22} & A_{m23} & 0 & A_{m25} \\ 0 & A_{m32} & 0 & 0 & 0 \\ A_{m41} & 0 & A_{m43} & A_{m44} & A_{m45} \\ A_{m51} & A_{m52} & A_{m53} & A_{m54} & A_{m55} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_5 \end{bmatrix} u \tag{E.2}$$

(for SVC stabilizer design)

From [30], full order observer is given as,

$$\dot{\hat{X}} = (A + MC)\hat{X} + Bu - mY \quad (E.3)$$

Where, M is a 5x1 vector to place poles of (A+MC) at any desired location.

$$M = [m_1 \quad m_2 \quad m_3 \quad m_4 \quad m_5]^t \quad (E\ 4)$$

For PSS design:

Output equation is given as,

$$y = [C_1 \quad 0 \quad C_2 \quad 0 \quad C_3]\ [\underline{x}] \quad (E.5]$$

Hence, observer equations are obtained as,

$$\hat{X}_1 = B_{11}\hat{X}_1 + B_{12}\hat{X}_2 + B_{13}\hat{X}_3 + B_{14}\hat{X}_4 + B_{15}\hat{X}_5 - m_1 y$$

$$\hat{X}_2 = B_{21}\hat{X}_1 + B_{22}\hat{X}_2 + B_{23}\hat{X}_3 + B_{24}\hat{X}_4 + B_{25}\hat{X}_5 - m_2 y$$

$$\hat{X}_3 = B_{31}\hat{X}_1 + B_{32}\hat{X}_2 + B_{33}\hat{X}_3 + B_{34}\hat{X}_4 + B_{35}\hat{X}_5 - m_3 y$$

$$\hat{X}_4 = B_{41}\hat{X}_1 + B_{42}\hat{X}_2 + B_{43}\hat{X}_3 + B_{44}\hat{X}_4 + B_{45}\hat{X}_5 + b_4 4 - m_4 y$$

$$\hat{X}_5 = B_{51}\hat{X}_1 + B_{52}\hat{X}_2 + B_{53}\hat{X}_3 + B_{54}\hat{X}_4 + B_{15}\hat{X}_5 - m_5 y$$

(E.6)

Where,

$$B_{11} = A_{m11} + m_1 c_1$$

$$B_{12} = 0$$

$$B_{13} = A_{m13} + m_1 c_2$$

$$B_{14} = A_{m14}$$

$$B_{15} = A_{m15} + m_1 c_3$$

$$B_{21} = A_{m21} + m_2 c_1$$

$$B_{22} = A_{m22}$$

$$B_{23} = A_{m23} + m_2 c_2$$

$$B_{24} = 0$$

$$B_{25} = A_{m25} + m_2 c_3$$

$$B_{31} = m_3 c_1$$

$$B_{32} = A_{m32}$$

$$B_{33} = m_3 c_2$$

$$B_{34} = 0$$

$$B_{35} = m_3 c_3$$

$$B_{41} = A_{m41} + m_4 c_1$$

$$B_{42} = A_{m42}$$

$$B_{43} = A_{m43} + m_4 c_2$$

$$B_{44} = A_{m44}$$

$$B_{45} = A_{m45} + m_4 c_3$$

$$B_{51} = A_{m51} + m_5 c_1$$

$$B_{52} = 0$$

$$B_{53} = A_{m53} + m_5 c_2$$

$$B_{54} = 0$$

$$B_{55} = m_5 c_3 \tag{E.7}$$

For SVC stabilizer design:

Output equation is given as,

(for both Midline active power and Midline reactive power signals)

$$y = [d_1 \quad 0 \quad d_2 \quad 0 \quad d_3] \ [\underline{x}] \tag{E.8}$$

Hence, observer equations are obtained as,

$$\hat{x}_1 = Q_{11}\hat{x}_1 + Q_{12}\hat{x}_2 + Q_{13}\hat{x}_3 + Q_{14}\hat{x}_4 + Q_{15}\hat{x}_5 - m_1 y$$

$$\hat{x}_2 = Q_{21}\hat{x}_1 + Q_{22}\hat{x}_2 + Q_{23}\hat{x}_3 + Q_{24}\hat{x}_4 + Q_{25}\hat{x}_5 - m_2 y$$

$$\hat{x}_3 = Q_{31}\hat{x}_1 + Q_{32}\hat{x}_2 + Q_{33}\hat{x}_3 + Q_{34}\hat{x}_4 + Q_{35}\hat{x}_5 - m_3 y$$

$$\hat{x}_4 = Q_{41}\hat{x}_1 + Q_{42}\hat{x}_2 + Q_{43}\hat{x}_3 + Q_{44}\hat{x}_4 + Q_{45}\hat{x}_5 - m_4 y$$

$$\hat{x}_5 = Q_{51}\hat{x}_1 + Q_{52}\hat{x}_2 + Q_{53}\hat{x}_3 + Q_{54}\hat{x}_4 + Q_{15}\hat{x}_5 + b_5 u - m_5 y$$

(E.9)

Where,

$$Q_{11} = A_{m11} + m_1 d_1$$

$$Q_{12} = 0$$

$$Q_{13} = A_{m13} + m_1 d_2$$

$$Q_{14} = A_{m14}$$

$$Q_{15} = A_{m15} + m_1 d_3$$

$$Q_{21} = A_{m21} + m_2 d_1$$

$$Q_{22} = A_{m22}$$

$$Q_{23} = A_{m23} + m_2 d_2$$

$$Q_{24} = 0$$

$$Q_{25} = A_{m25} + m_2 d_3$$

$$Q_{31} = m_3 d_1$$

$$Q_{32} = A_{m32}$$

$$Q_{33} = m_3 d_2$$

$$Q_{34} = 0$$

$$Q_{35}\ m_3 d_3$$

$$Q_{41} = A_{m41} + m_4 d_1$$

$$Q_{42} = 0$$

$$Q_{43} = A_{m43} + m_4 d_2$$

$$Q_{45} = A_{m44}$$

$$Q_{45} = A_{m45} + m_4 d_3$$

$$Q_{51} = A_{m51} + m_5 d_1$$

$$Q_{52} = A_{m52}$$

$$Q_{53} = A_{m53} + m_5 d_2$$

$$Q_{54} = A_{m54}$$

$$Q_{55} = A_{m55} + m_5 d_3 \qquad \text{(E 10)}$$

For different signals under consideration, different vectors M are selected to design observer keeping in mind the important criterion of stability and using separation principle [29] & [30].